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TECHNICAL REPORT 87-24

Crosshole Investigations – Details of the Construction and Operation of the Hydraulic Testing System

D. Holmes
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ABSTRACT

The Crosshole Programme, part of the international Stripa Project is designed to evaluate the effectiveness of various remote-sensing techniques in characterising a rock mass around a repository. A multidisciplinary approach has been adopted in which various geophysical, mapping and hydrogeological methods are used to determine the location and characteristics of significant features in the rock. The Programme utilises six boreholes drilled in a fan array from the 360 metre level in the Stripa Mine, Sweden.

The hydrogeological component of the work uses single and crosshole testing methods, including sinusoidal pressure testing, to locate fractures and characterise groundwater movement within them. Crosshole methods use packers to isolate portions of two boreholes which both intersect a significant feature in the rock mass. Hydraulic signals are generated in one isolated section and received in the other borehole. This report describes the design and operation of the computer-controlled system which automatically performs the hydrogeological tests.

Key words : Hydrogeological testing, equipment, mines, single hole testing, crosshole testing, sinusoidal testing.

RESUME

Le programme d'études "crosshole", qui constitue une partie du Projet international Stripa, est conçu pour évaluer l'efficacité de diverses techniques de détection à distance ayant pour objectif la caractérisation de la masse rocheuse entourant un dépôt final. Une approche multidisciplinaire a été adoptée mettant en oeuvre diverses techniques géophysiques de cartographie et méthodes hydrogéologiques pour localiser et caractériser les principales zones de perturbations dans la roche. Le programme utilise un réseau de six forages réalisés en éventail à partir du niveau 360 mètres dans la mine de Stripa en Suède.

La partie hydrogéologique de ce programme comprend des essais réalisés en puits unique et entre plusieurs puits (par exemple des essais sous pression sinusoïdale) qui permettent de localiser les fractures et d'y caractériser le mouvement des eaux souterraines. La méthode "crosshole" utilise des "packers" (obturateurs) pour isoler dans deux forages les sections qui sont traversées par une même zone de fracture. Des signaux hydrauliques sont générés dans l'une des sections isolées et perçus dans l'autre. Ce rapport décrit la conception et l'exploitation du système géré par ordinateur qui réalise automatiquement ces essais hydrogéologiques.

ZUSAMMENFASSUNG

Das geophysikalische "Crosshole"-Programm, welches Teil des internationalen Stripa-Projekts ist, hat zum Ziel verschiedene Erkundungs-Methoden zur Ermittlung von Gesteinseigenschaften zu überprüfen. Es wurde ein interdisziplinäres Vorgehen verwendet, das sich auf geophysikalische, geologische und hydrogeologische Methoden abstüzt zur Lokalisierung und Charakterisierung der wichtigsten Strukturen im Gestein.

Zur Durchführung des Programmes wurden sechs Bohrlöcher verwendet, die auf der 360 m Sohle der Stripa Mine fächerförmig abgeteuft wurden.

Um Klüfte zu lokalisieren und deren hydraulische Eigenschaften zu studieren, werden bei den hydrogeologischen Untersuchungen "single-" und "crosshole-testing"-Methoden angewandt. Dazu werden mit Hilfe von Packern bestimmte Kluftabschnitte zwischen zwei Bohrlöchern isoliert. Sinusförmige Druckpulse werden in einem Bohrloch erzeugt (sinusoidal pressure testing) und deren hydraulische Signale werden in einem benachbarten Bohrloch empfangen. Diese Registrierungen werden dann zur Ermittlung der interessierenden Parameter verwendet.

Der Bericht enthält die Beschreibung des computer-gesteuerten Systems zur automatischen Durchführung der hydraulischen Tests sowie einen Beschrieb des generellen Vorgehens bei den Untersuchungen.

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SUMMARY

This report is one of a series which describes work undertaken by the British Geological Survey for the Stripa Project. The work forms part of the Crosshole Programme, which is a multidisciplinary approach to rock mass assessment around a potential repository, using radar, seismic and hydrogeological techniques.

Hydrogeological characterisation has been attempted using the sinusoidal pressure test, in addition to more standard methods, in six boreholes drilled, as a fan array, from the 360 m. level in the mine. Equipment has been designed to generate a hydraulic signal (source borehole) and monitor its progress through the rock mass (receiver borehole).

The equipment design was influenced by the hydraulic conditions expected in the local rock environment. Of major importance is the field of hydraulic pressure caused by groundwater draining into the mine cavities. This field varies considerably and has necessitated the design of a testing system which is extremely adaptable in generating and observing variations in flow and pressure.

The equipment is rugged and can operate successfully in the mine at pressures from 0 to 35 Bar. Computer control of the testing allows the system to operate for extended time periods and provides great flexibility in performance. Data storage and processing are made relatively easy. Procedures have been developed to enable single borehole transient as well as crosshole sinusoid and constant rate testing.

1. INTRODUCTION

As part of an international research programme into the disposal of radioactive wastes in deep geological environments a series of crosshole experiments have been initiated at the Stripa mine, Sweden. Some 3 million cubic metres have been penetrated by a fan array of six boreholes. In these various geophysical techniques (radar and seismic) are used to characterise the rock and hydraulic techniques are employed to characterise groundwater movement within this volume.

Flow through the crystalline rock mass occurs via the fractures. The geophysical techniques can locate single fractures, or closely spaced groups of fractures, and indicate where they intersect the array of boreholes. The hydraulic testing is designed to show how significant these features are within the general flow pattern by measuring transmissivities and flow pathways. Transmissivity is a measure of the volume of water which can be transported through the rock under a unit gradient. The hydraulic tests may also indicate some features which are not detected by the geophysical methods.

Compared to hydraulic testing methods geophysical techniques are rapid to execute and can examine a large volume of rock, comprehensively, over a period of only a few months. A less detailed characterisation using hydraulic tests may take several years. Comparisons of the results obtained during the crosshole programme will determine the ability of the geophysical techniques to locate those parts of the rock mass in which most of the groundwater flow occurs. If the techniques are proved reliable, it may be possible to reduce the amount of hydraulic testing required during the site investigation for a repository. However, some hydraulic testing would always be needed to quantify the flow rates and determine flow directions.

The hydraulic testing component of the crosshole investigation involves the transmission of various hydraulic signals between two or more boreholes. As the signal passes through the water bearing rock it is modified by the interaction between fractures and rock matrix. Mathematical interpretation of signal attenuation allows various relevant hydrogeological parameters to be quantified, in particular that of hydraulic diffusivity (Black and Barker (1982) and Black *et al.*, (1986)).

The testing system is designed to operate at the 360m. level in the Stripa mine, but is equally suited to perform hydrogeological measurements in any mine cavity in which water pressures exceed atmospheric pressure. The problems of working in such an environment have been detailed in Holmes (1984) but are outlined below.

Both the signal generating system (source borehole) and measuring equipment (receiver borehole) must be sufficiently adaptable to cope with the range of pressures found in the mine. The mine greatly modifies any large scale regional pressure field by acting as a drain, creating possible pressures from 1 to 35 Bars at the 360m. depth. Encountered pressures have ranged between -3 and 10 Bars. In addition to the absolute pressure, the receiver system must be capable of measuring, accurately, signals not exceeding 0.001 Bar relative to the prevailing pressure. The system also needs to be rugged and automated to run for extended periods without supervision. It should also sense any problems occurring during the testing and react by aborting the test safely.

The testing system was commissioned in the Stripa mine in late summer, 1984 and has performed a series of single and crosshole experiments since that date. Improvements have been made to the hardware and software to increase its "user friendliness" and data handling capabilities.

During crosshole testing packers are positioned in one borehole to isolate a specific zone (source zone) in which hydraulic signals can be generated to be transmitted through a feature in the rock. In another borehole, a group of packers are installed to isolate several zones (receiver zones) in which the signals can be detected.

This report provides a relatively detailed description of the equipment and software which comprise the hydraulic testing system. Some details are also provided on how the system is used to perform various hydrogeological tests.

2. EQUIPMENT AND DESIGN OF THE TESTING SYSTEM

2.1 Introduction

This section of the report provides information on the equipment which makes up the hydraulic testing system. Electronics and hydraulics are combined in a novel way to produce a versatile testing system. Firstly, there is a general description of the equipment and how it operates. This is followed by details of the various individual components.

2.2 General equipment description and function

All the equipment is self-contained and housed in the mine working area of the SGAB Drift some 360 metres below ground level. The drift has been excavated to provide a cavity some 20 m. long by 10 m. wide. From one wall are drilled 6 boreholes in a fan array. At the mine wall the boreholes are separated by approximately 1 m. but as they are drilled at different angles, the separation distance increases to a maximum of 250 m. at their furthest extent. During testing the packer assemblies for the source and receiver boreholes are located in two boreholes. The various pumps, valves and inflation equipment are positioned in the mine cavity only some metres from the boreholes. A large cabin, constructed in one corner of the mine cavity, provides protection for the main control cabinet and microcomputer. The mine area is provided with a 35 Amp, 3 phase power supply and piped water.

The source borehole (figure 1) contains two hydraulically inflated packers, which can be separated to produce a test zone which is from 1 to 20 metres in length. A rod string is used to position these and connects the source zone, between the packers, to pumps which inject or abstract water to create any required variation in pressure (called the hydraulic signal). The source zone pressure is monitored by a 35 Bar transducer located down-hole, immediately adjacent to the test section. A by-pass tube through the packer assembly connects the two lengths of borehole either side of the packers, jointly termed the rest-of-borehole zone. A transducer (35 Bar) measures the pressure of this zone.

All the rods, tubes and cables pass through a tapered sealing manifold. This device is bolted onto a flanged pipe which is grouted into the end of each of the boreholes within the array. Rubber elements are compressed by a pressure plate and seal around the pipes and tubes passing through the manifold. They can operate to a maximum pressure of 40 Bars and stop the source borehole from loosing pressure by water draining into the drift. The manifold is removed to re-locate the either packer assembly, but can be refitted within 10 minutes. All the boreholes are sealed by plates during testing and their pressures monitored by 35 Bar transducers.

Two pumps are operated in the mine working area. One injects or abstracts water from the source zone, under computer command, to generate hydraulic signals. The other responds to pressure changes in the rest of borehole zone caused by water flowing around the isolating packers. Any pressure fluctuations are damped out to ensure that the hydraulic signal originates from the source zone and is not derived from the leakage of the signal to

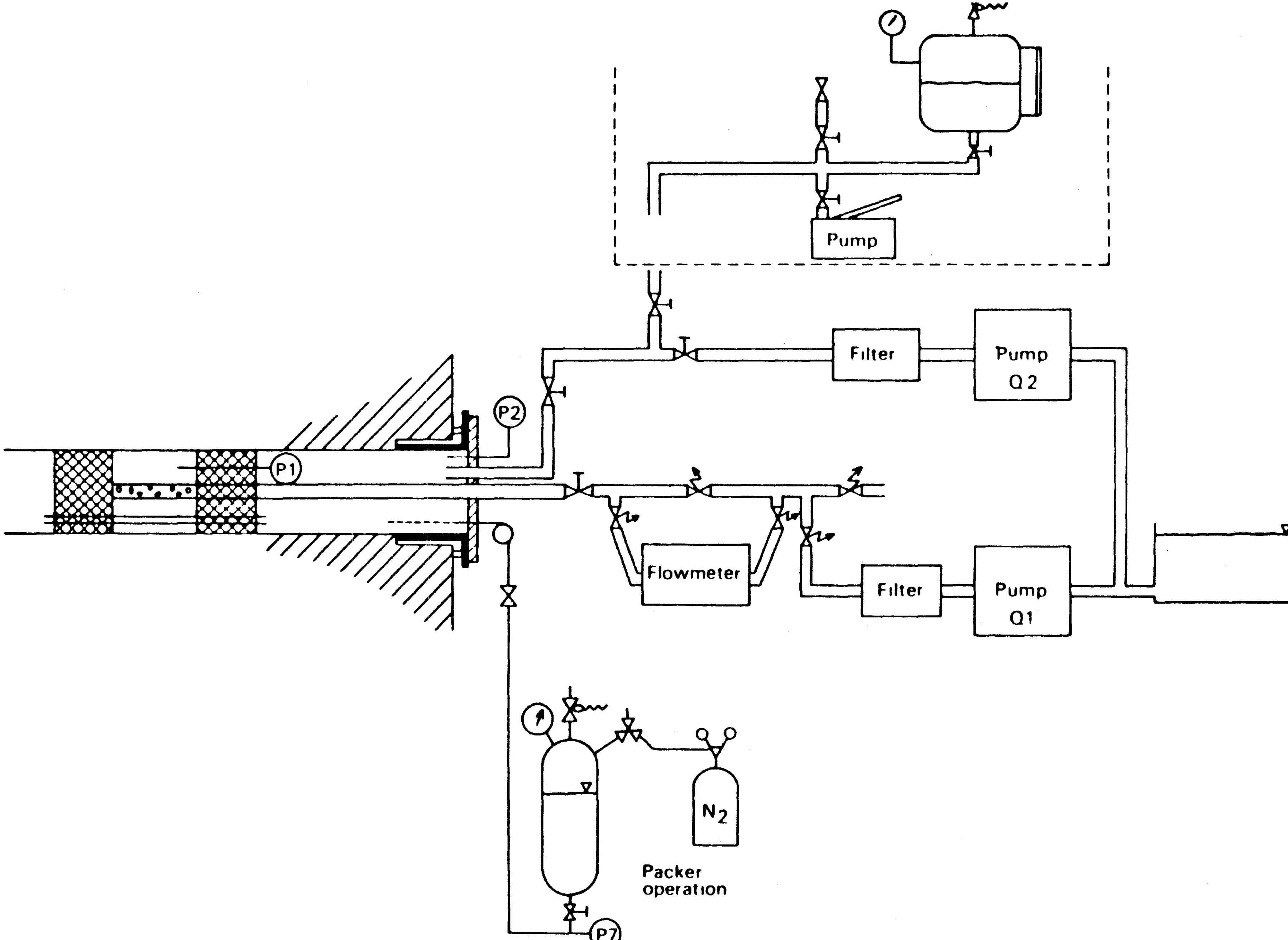


Figure 1 **Source borehole equipment**

the rest of borehole zone. Both pumps are, however, identically constructed. Each comprises a finely machined cylinder with a tightly fitting double-acting ram. This water pump is moved by a direct-coupled, hydraulic-augmented mechanical driving ram, the exact linear position of which is controlled by a stepping motor. Solenoid valves are fittted to the entrance and exit ports of the water cylinder to control the direction of flow, either into the borehole or to a storage reservoir. One step of the motor is 0.033 cm^3 of water. The flow rate ranges between 0.033 and 3000 cm^3/minute at up to 40 Bars, at which a pressure relief valve operates to protect the system against overpressurisation.

Each pump has an "on board" microprocessor, acting as an interface, which accepts commands from the central microcomputer to increase or decrease the flow rate. These are interpreted to vary the stepping rate and solenoid status to provide the required rate and direction of flow. The motor stepping rate is recorded by the control computer as a direct measure of flow rate, assuming there is no leakage around the water ram. To date only very small leakage rates have been detected. Filters are provided to protect the pumps against particulate material which could damage the ram seals.

The receiver borehole (figure 2) contains six hydraulically inflated packers which isolate five short and two long zones. Each of these is connected to the mine area by a water filled pressure tube. The packer assembly is positioned by a "blank rod string" using a hydraulically powered handling device. All the tubes emerge from the borehole through a tapered sealing manifold, similar to the one on the source borehole, and continue to a "pressure measuring board".

The board comprises a group of solenoid-actuated valves and pressure transducers. The tube from each zone is isolated from the "pressure measuring board" by a solenoid-actuated "access valve". The pressure in the tube is measured by opening the appropriate "access valve" and hence connecting the tube directly to an absolute pressure transducer with a range up to 35 Bar. For more detailed measurement two differential transducers (1 and 7 Bar), which measure zone pressure relative to a variable reference pressure, are located in the system. The reference pressure is contained in a "reference pressure tube" which is actually a long plastic tube installed in a nearby mine shaft. The column of water in this tube, which has a free upper surface, can be varied in height to match the pressure in the receiver zones. This pressure is measured by another 35 Bar transducer.

The differential transducers allow zone pressures to be measured to a greater accuracy than

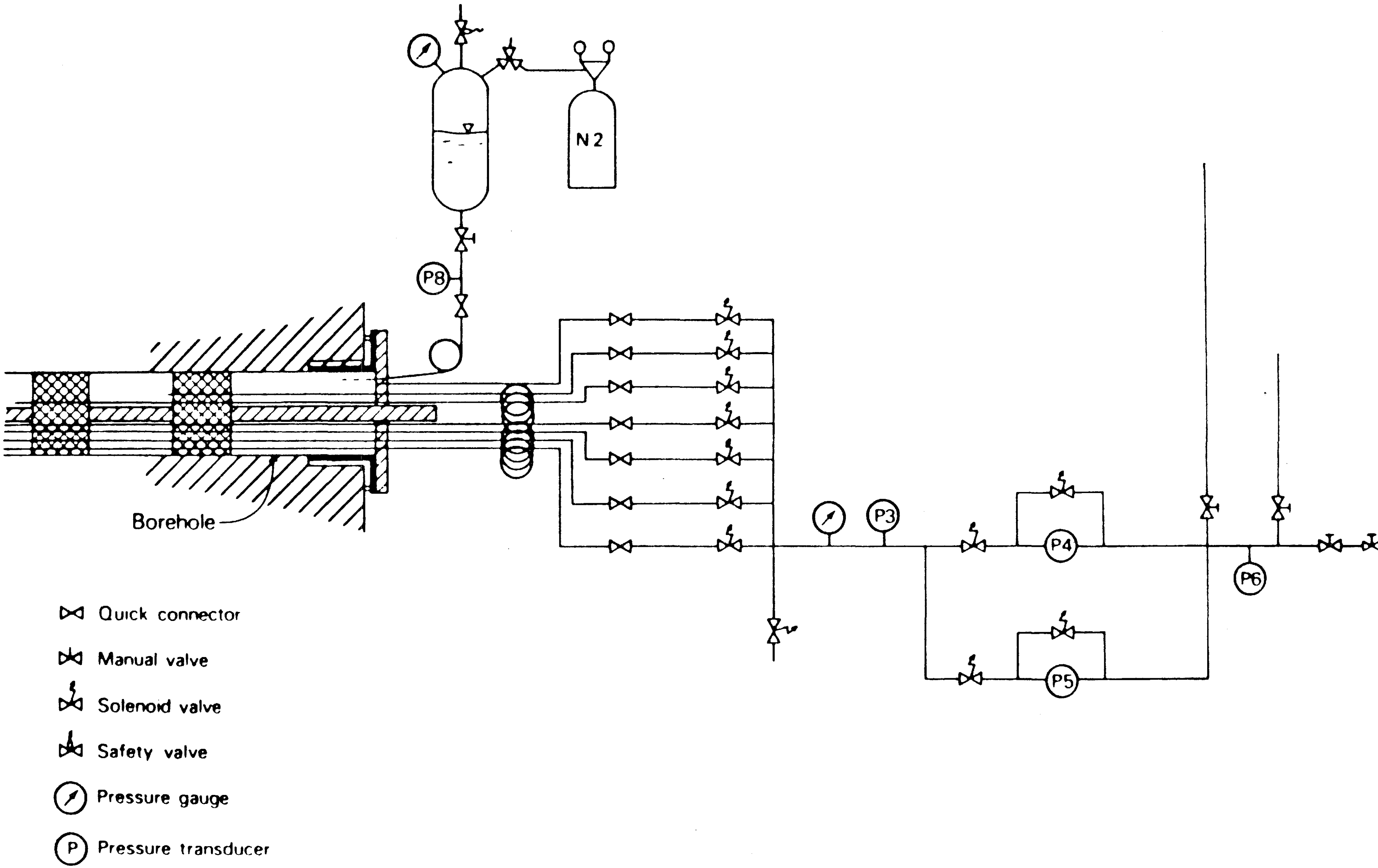


Figure 2 Receiver borehole equipment

is possible using absolute transducers. The 35 Bar (~350 m. water equivalent pressure) instrument can resolve to 0.1 metres with an accuracy (non-linearity and hysteresis) of +/-0.2m.. However, these values are 0.01 m. and 0.04 m. for the 7 Bar and 0.001 m. and 0.006 m. for the 1 Bar differential transducers. The reference pressure allows this accuracy to be maintained over a 0 to 35 Bar absolute pressure range. The differential transducers are easily damaged by excess pressure and need to be protected from connection to extremely different pressures.

Reading the pressure of each receiver zone follows an identical pattern, controlled by the main computer. Firstly the solenoid-actuated valves for a particular zone is opened to connect that zone to the absolute transducer. This pressure value is then compared to a pressure reading obtained from the reference tube. If they lie within 7 Bars, the 7 Bar differential transducer is switched into the measuring loop. Normally both differential transducers are isolated from the measuring loop and the pressure is balanced across the measuring head. If the pressure difference is less than 1 Bar, the 1 Bar differential instrument can be read. This process is repeated for each preselected zone pressure until a scan of all the zones has been completed.

A disadvantage of this system is the time required to complete a scan which may approach several minutes. However, this is offset by the accuracies attained and the lack of transducer drift owing to the use of one transducer and the reference pressure.

The packers in both the source and receiver boreholes are inflated by a water system with a gas overpresure to a pressure of about 20 Bar in excess of the environmental pressure. Each inflation system is monitored by a 70 Bar transducer which is read by the central computer. Alarm values can be set by the operator (maximum or minimum) which, if passed, cause the computer to issue warnings. If no action is taken the testing system is automatically closed down. All the solenoid-actuated valves are closed to isolate the boreholes from water inflow or outflow. Thus, water will not drain into the mine causing borehole pressures to fall. Similar action results if there is a power failure in the mine.

The control system is shown diagrammatically in Figure 3. It comprises a central Z80-based microcomputer driving a group of intelligent peripherals. The pumps and transducers are operated via processor-based units responding to simple command strings. This frees the central computer from time consuming control functions. Data are stored on floppy disc and can also be presented in "real time" on a matrix printer in graphical form. Most of the programming is in Pascal MT+ to facilitate data handling.

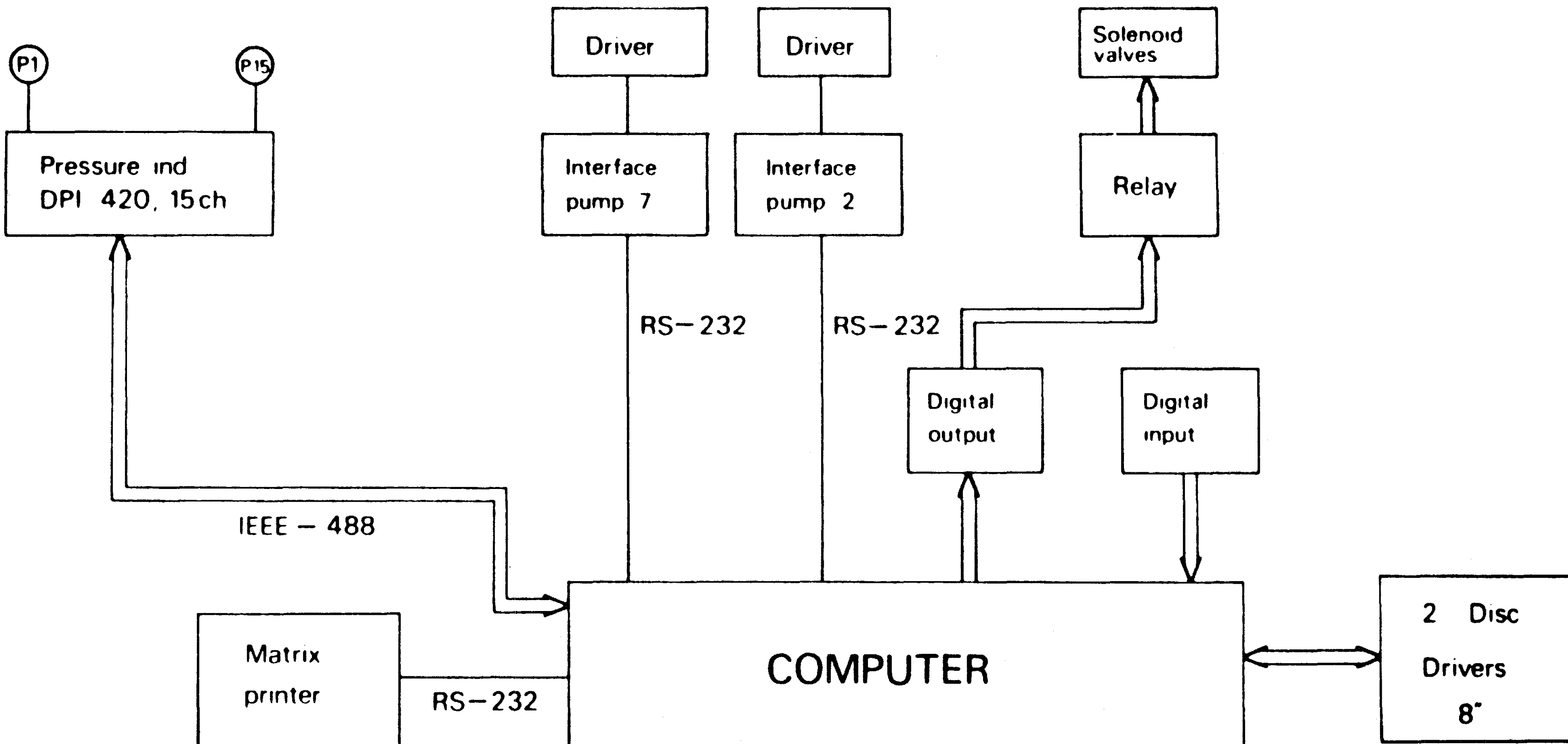


Figure 3 Generalised control system

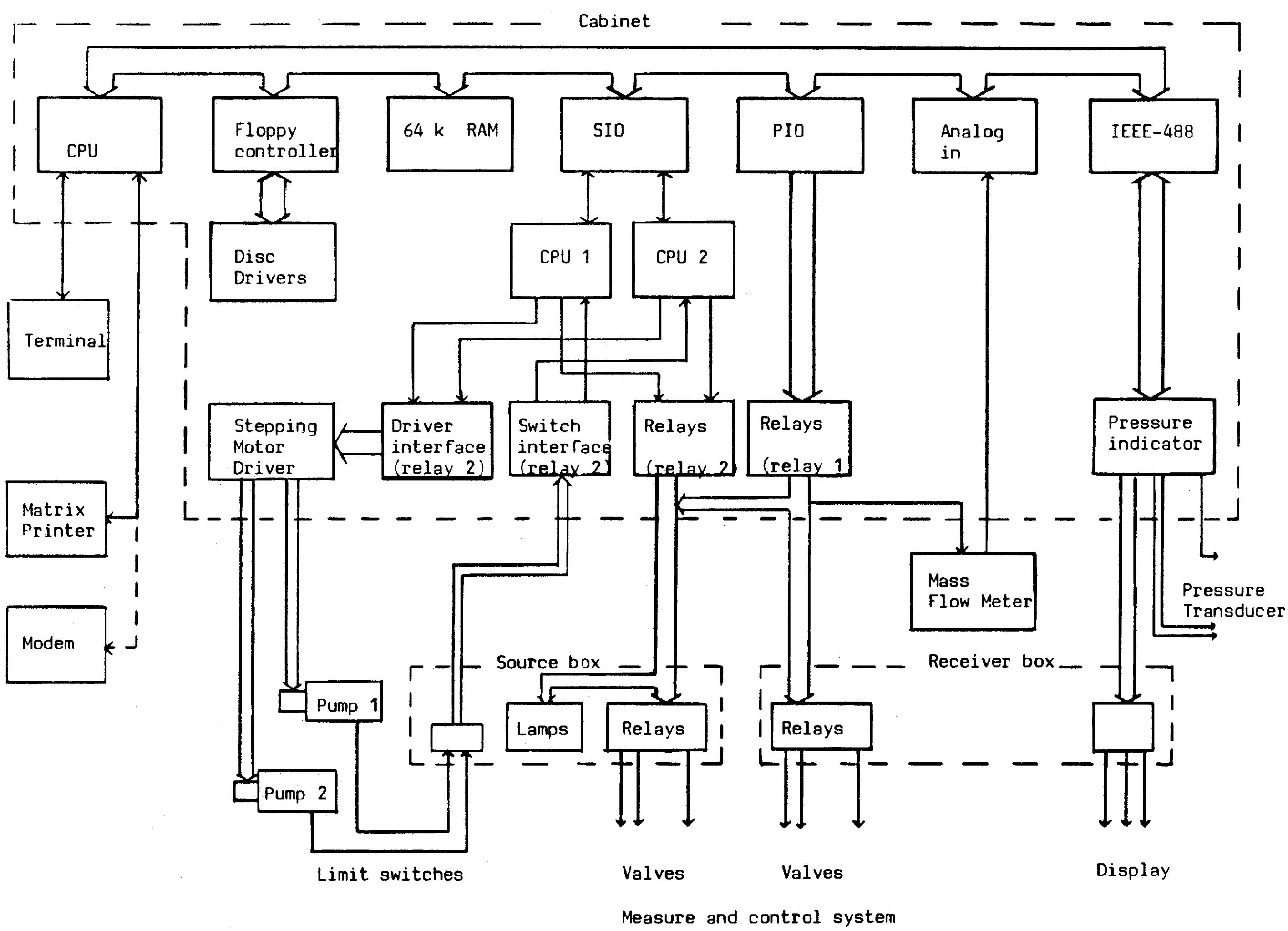


Figure 4 **Detailed control system**

The key element in testing is the ability of the control system to generate the hydraulic signal in the source zone. The central computer calculates a predicted curve of given shape (sinusoidal, square, constant rate etc.) based on information (amplitude, frequency etc.) provided by the operator. In the control cycle the computer compares the measured source zone pressure to the predicted and commands the pumps to increase or decrease the injection or abstraction rate to follow the curve. During testing this cycle is repeated, on average, every ten seconds. The rest-of-borehole pressure is controlled in a similar manner.

2.3 Component details

This section provides detailed information on various components of the system. Where applicable notes are provided on problems encountered under operating conditions and how they were overcome. Some improvements are also suggested which would be applied to any new testing system.

2.3.1 Measure and control system

This is the "brain" of the testing system which controls all the equipment and measures pressures via the transducers. Figure 4 shows the lay-out of the system in diagrammatic form.

Much of the hardware (board-mounted electronics and connectors) is housed in a standard 19 inch cabinet within the mine hut to protect it, as far as possible, from the cold, dusty and damp environment experienced in the mine. The cabinet itself is cooled by a powerful fan which passes a filtered supply of air over the electronics. Power (220 volt) is supplied to the cabinet through a transformer which protects the system against voltage fluctuations.

2.3.1.1 Electronics

The core of the controller is a Z-80 Central Processing Unit (CPU) based computer linked, by a parallel bus, to the floppy disc controller, 64 k RAM, a Serial Input/Output (SIO), a Parallel Input/Output (PIO), an analogue and an IEEE-488 interface card. The disc controller interfaces to a twin 8 inch drive unit for the storage of programs, in drive A, and data, in drive B. The RAM provides operating space for the programs. Input/output cards allow the computer to communicate with the pumps and open and close solenoid valves. An additional analogue card receives information from the flow meter. Finally, there is the

IEEE interface which controls and receives pressure data from the pressure transducers via the DPI-420 indicator unit. The computer is also connected, by RS-232, to a Visa 30 Terminal/ Visual Dispay Unit and, by a separate port, to an Epson MX 100 dot matrix printer. This port also supplies a route to a modem for data transmission to another remote computer.

The SIO card links to two dedicated Z-80 CPU cards, which act as interfaces to each of the pumps. Each has its own in-built programming stored on Rom to execute commands sent by the computer. They communicate with the stepping-motor drivers of the pumps and to solenoid actuated valves,which control the direction of water flow on the source board, through booster relays. These are necessary to convert the low power 0 - 5 volt signals from the pump interfaces to 0 - 24 volt DC signals which can be transmitted to the source board via cables. The 24 volt transformer is housed in the control panel of the source board. The PIO card links to the solenoids on the receiver board also via a boosting relay. Additionally, the pump interfaces can receive interrupt signals from limit switches on the pumps. These are a safety feature to protect the pump mechanism.

The IEEE-488 card allows rapid communication with the DPI-420 pressure indicator. This has 15 channels of input from the transducers and can provide 15 channels of analogue output. Three of these are sent to digital read-outs on the receiver board to provide a continuous display of the zone, reference and 7 Bar differential pressure transducer readings. Other transducers can be read by manually selecting a channel from a key pad on the DPI-420.

2.3.1.2 Pressure transducers

A number of transducers were supplied to measure pressures in a variety of locations within the testing system. Each was calibrated at the point of manufacture to a particular channel in the DPI-420. Each transducer type and its location are listed below.

i) Two Druck (manufacturer) PDCR 10/D transducers fitted with 250 metres of electrical cable. These operate from 0 to 35 Bar and are used to measure the down-hole source zone pressure. One was intended as a spare but was used to measure the rest-of-borehole pressure.

ii) Seven Druck PDCR 100/W transducers operating from 0 to 35 Bar. These are located on four of the observation boreholes, and two on the receiver board to measure the zone and reference pressures. One is a spare.

iii) Two Druck PDCR 100/W transducers operating from 0 to 70 Bar with one located on each of the inflation cylinders for the source and receiver packer probes, to monitor inflation pressure.

iv) Two Druck PDCR 120/WL transducers to measure differential pressure, on the receiver board, from 0 to 7 Bar. One as a spare.

v) Two Druck PDCR 120/WL transducers, also on the receiver board, to measure differential pressure from 0 to 1 Bar. One as a spare.

2.3.1.3 Problems

In general the elctronic measurement and control equipment operated well. However, there were a few components which caused concern.

The power supply to the mine area was more prone to interruption than had been expected during the design phase. Any interruption greater than 0.5 seconds caused the computer to crash, stopping any test which was in progress. This could be remedied by installing a battery powered back-up system.

Some testing time was lost due to failures in the disc drive units, which had to be sent away for repair. However, they lasted longer than expected in the mine environment.

Greater time was lost through the breakage of the DPI-420 unit in which two faults developed simultaneously. Firstly, the internal IEEE card failed, so stopping all communication with the unit. Secondly, the system experienced a magnetic pulse during an electrical storm. This destroyed the two transducers with long cables and parts of the calibrated circuitry in the DPI-420. No other electronics were affected. The loss of the two transducers, usually employed down-hole, required that source pressures were measured at the top of the borehole through an improvised pressure port.

2.3.2 Source borehole equipment

This comprises all components of the testing system which are involved with controlling pressures in the source borehole including the source board, the two pumps, the packer probe and its inflation system, the borehole capping assembly and the water supply to the pumps. All components attached to the borehole are designed to operate to a maximum pressure of 35 Bar.

2.3.2.1 Source board

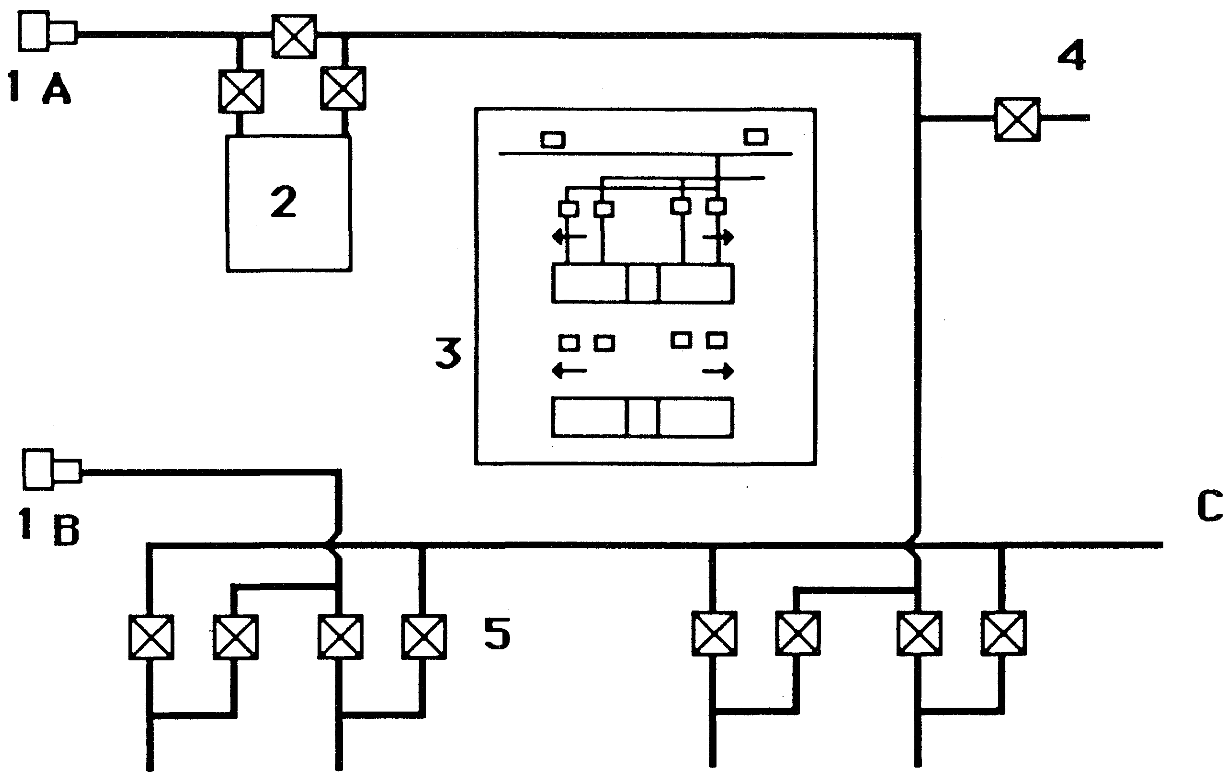
This is a large board some 1.5 m. long and 1 m. high onto which are fitted solenoids, steel flow pipes, a flow meter and a control panel. The lay out is designed in a logical manner to show the function of each flow path so that fault finding is simplified. Three flow paths are represented on the board. Firstly, there is the path from the mine water supply to the pumps. Secondly, the path for the source zone pump to the borehole and, thirdly, the path from the rest of borehole pump to the borehole. Each flow path contains in-line filters to stop particulate matter of greater than 0.1 µm entering the pumps and solenoids which could cause damage. Figure 5 is a diagrammatic representation of the source board.

All the solenoid valves are rated to 40 Bar and require a 220 volt power supply. The central control system provides a 24 volt signal to relays in the board control panel which is boosted to the required level. The valves are designed to operate efficiently in one direction. Therefore, two back-to-back valves are used in locations where flow can be in both directions.

12 mm. diameter stainless steel tubing is used to form the flow paths. All connections to solenoids and tee-pieces are made with standard compression fittings. Thus, if a solenoid valve is damaged it can be replaced relatively easily.

The flow meter is of a mass flow type and can measure from 0.05 to 1 litre/minute to an accuracy of 0.4%. At lower flows the accuracy is slightly reduced. It produces a 0 to 5 volt analogue signal which is proportional to flow but independent of flow direction. The meter is mounted on the board with associated solenoid valves so that it can be isolated from the source section flow stream when not required.

The control panel contains the booster relays and power supply for the solenoid valves. Each valve is also connected to a display lamp in a pictogram which shows all the flow



Legend

1 Quick-fit connector
2 Mass flow meter
3 Control panel
4 Pulse solenoid valve
5 Solenoid valve

A Flow to source section
B Flow to rest-of-borehole section
C Flow to water storage

Figure 5 Diagram of source board

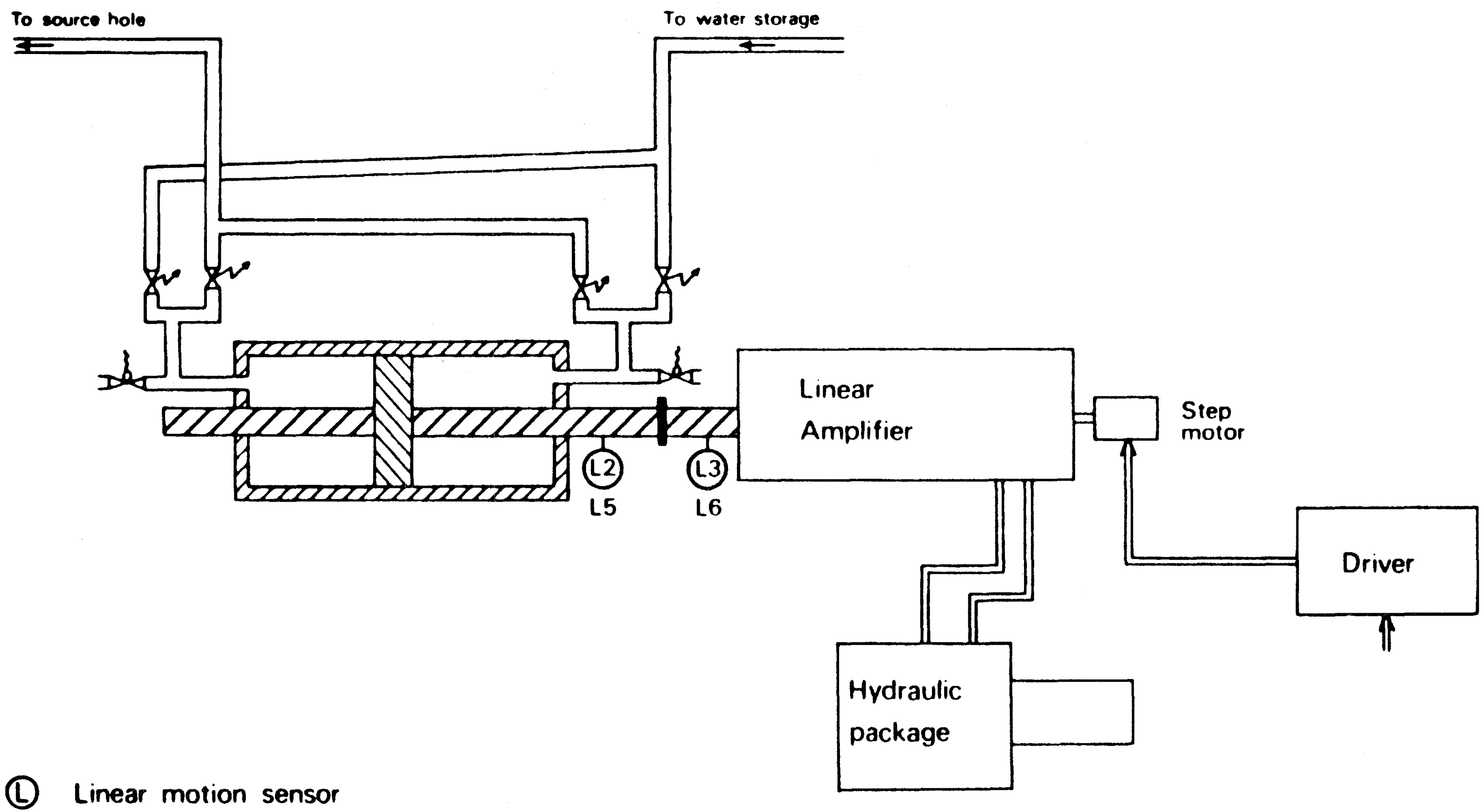


Figure 6 Pump design

paths on the board. Thus the operator can rapidly examine the pictogram to observe the status of each valve and the direction of pumping.

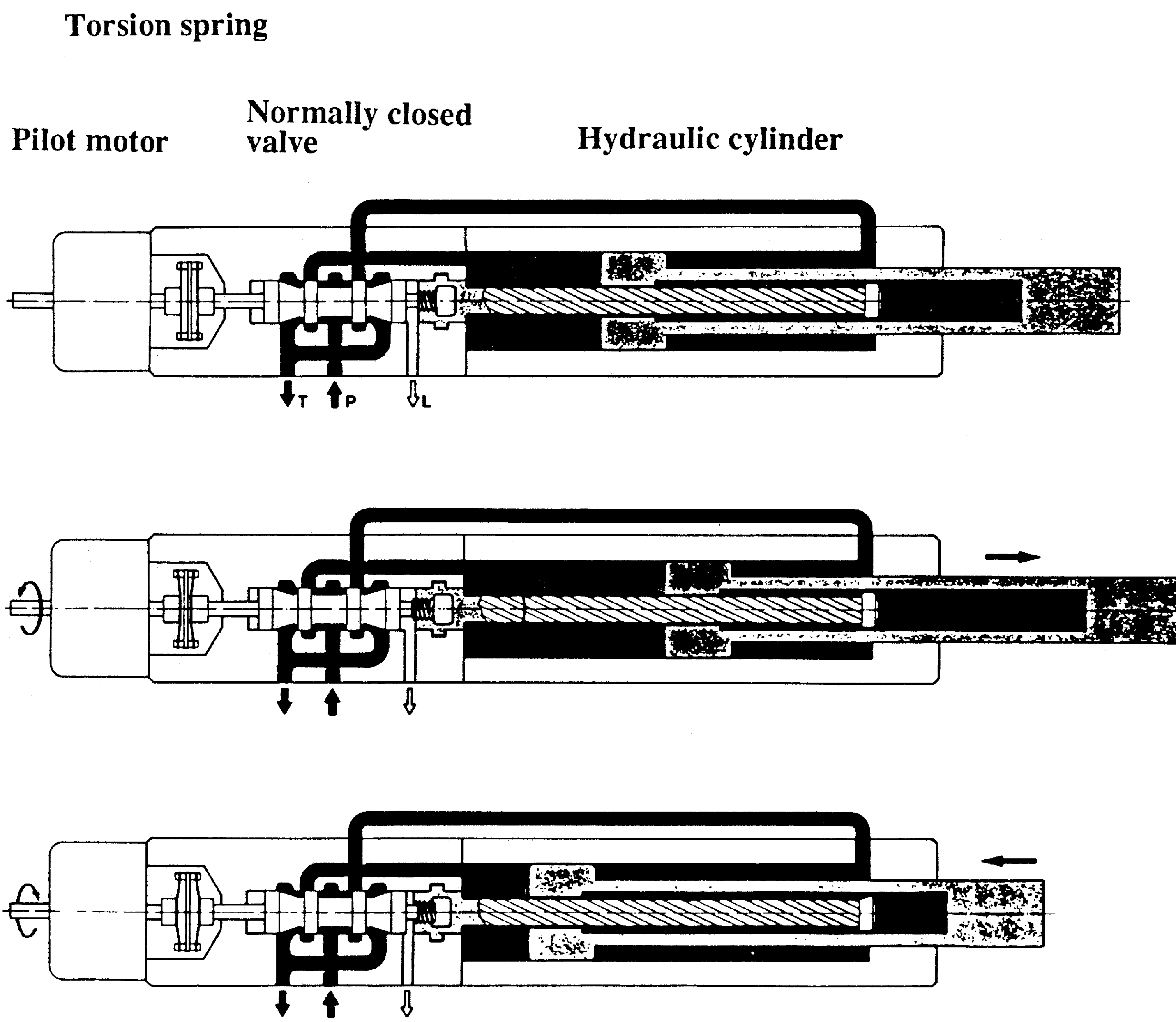
2.3.2.2 The pumps

There are two pumps, one to supply flow to the source section and the other to the rest-of-borehole. Both are identical in construction and operation comprising a commercially available hydraulic linear amplifier connected to a reciprocating water pump, manufactured specifically for SGAB. These two units are mounted on a rigid steel frame to ensure the correct linear alignment of the rams, as shown in figure 6. This is essential to minimise wear of the internal seals. The rams are joined by flanges which are torque adjusted for small alignment changes. Two miniature contact switches are mounted between the units so that they will be struck by the flange if the rams exceed their normal operating range. The whole pump assembly is about 2 metres long and must operate whilst horizontal.

The pumps only generate a specific flow rate. The direction of flow, either into or out of the borehole, is controlled by solenoid valves on the source board. These are under the control of the pump interfaces.

Figure 7 shows the design and operation of a linear amplifier. It comprises a stepping motor, torsion spring, spooling valve and hydraulic cylinder. Hydraulic power is supplied to the cylinder from a hydraulic power pack producing 10 litres/minute flow at 70 Bar. The power pack consists of an electric motor turning a hydraulic generator. The ram of the linear cylinder is positioned by a spiral thread turned by the stepping motor. The stepping motor also actuates a torsion spring which pushes or pulls at the spooling valve to direct hydraulic fluid to one end of the ram or the other. Thus the ram has great positional accuracy but can also produce a lot of force. Each step of the motor moves the ram 0.02 mm. and its absolute position is known to within 0.05 mm.. Any leakage of hydraulic fluid around the ram does not effect its positional accuracy.

The water pump is manufactured to very high tolerances to minimise leakage of fluid. The stepping rate is used as a measure of the flow rate so that any leakage will lead to errors in the apparent flow rate. The pump, shown in figure 8, is a well-machined cylinder with end seals and a ram seal rigidly fixed to a solid central ram arm. The end seals incorporate a wiper seal, two water step seals and a bearing tape seal which takes the weight of the central ram. The ram arm is of circular section and made from stainless steel. To it is



Legend

P Fluid supply
T Fluid return
L Valve leakage return

Figure 7 Design of linear amplifier

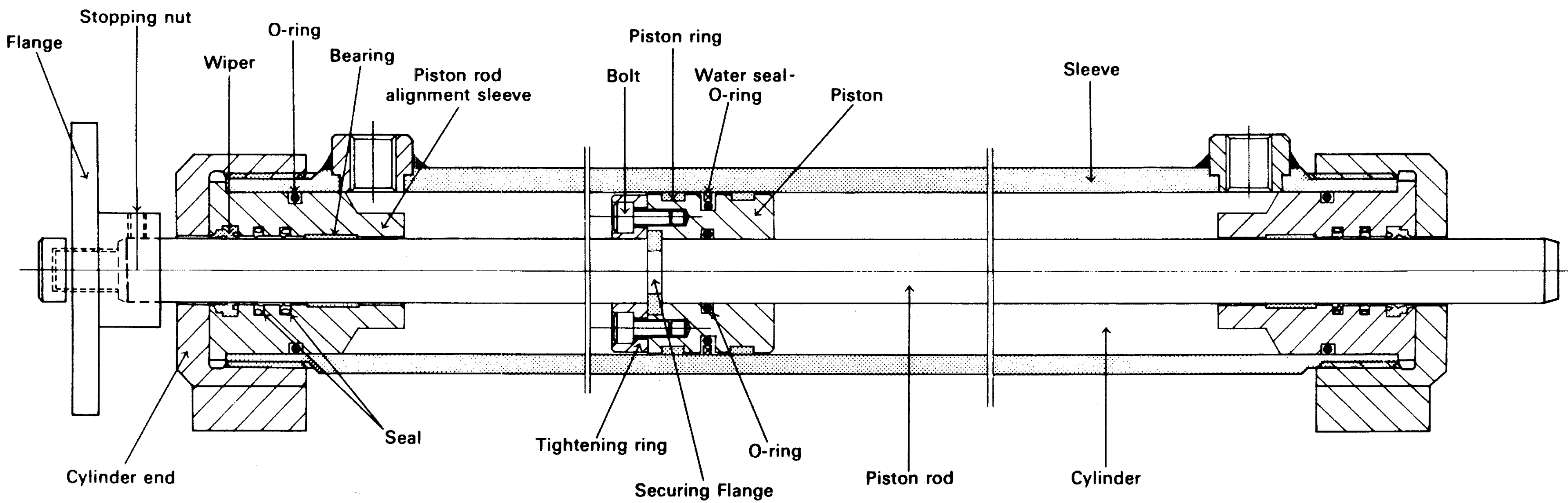


Figure 8 **Design of water pump**

fixed the ram itself, which incorporates two wiper seals and a special o-ring seal. The cylinder is 50 mm. in diameter and has a stroke of 530 mm.. At each end there is a port which connects by flexible hydraulic hose to the source board. Safety relief valves, set to open at 35 Bar, are fitted into the hoses as a final protection against overpressurising the system. An error signal is generated if any of these valves are opened.

As leakage of the water pump is so critical to the testing, methods were devised to assess its magnitude in the mine. If the leakage rate is too high on one of the pumps they can be swapped so that the better one is connected to the source zone. This allows testing to proceed until the pump can be repaired during a maintenance period. Water leaking from the end seals is easily spotted and measured. Leakage around the central ram cannot be directly observed. The first method involves pumping against a fixed pressure without generating a flow. The pump output line from the source board is disconnected from the borehole and connected to a sealed reservoir, the pressure of which can be measured by a transducer. A constant pressure test is initiated on the computer to maintain a pressure of 5 Bar in the reservoir. Any flow rate recorded by the test, when there is no real flow, is a measure of the leakage rate. The second method is a static test when the ram is not moving. The water pump cylinder is disconnected from the source board at the pressure ports. Water is injected into one port, using the packer inflation system, at a range of pressures. Any water leaking past the central ram will issue from the other port and can be measured.

2.3.2.3 The packer probe

This comprises the equipment which fits into the source. It includes the packers, rods and transducers to isolate the test zone.

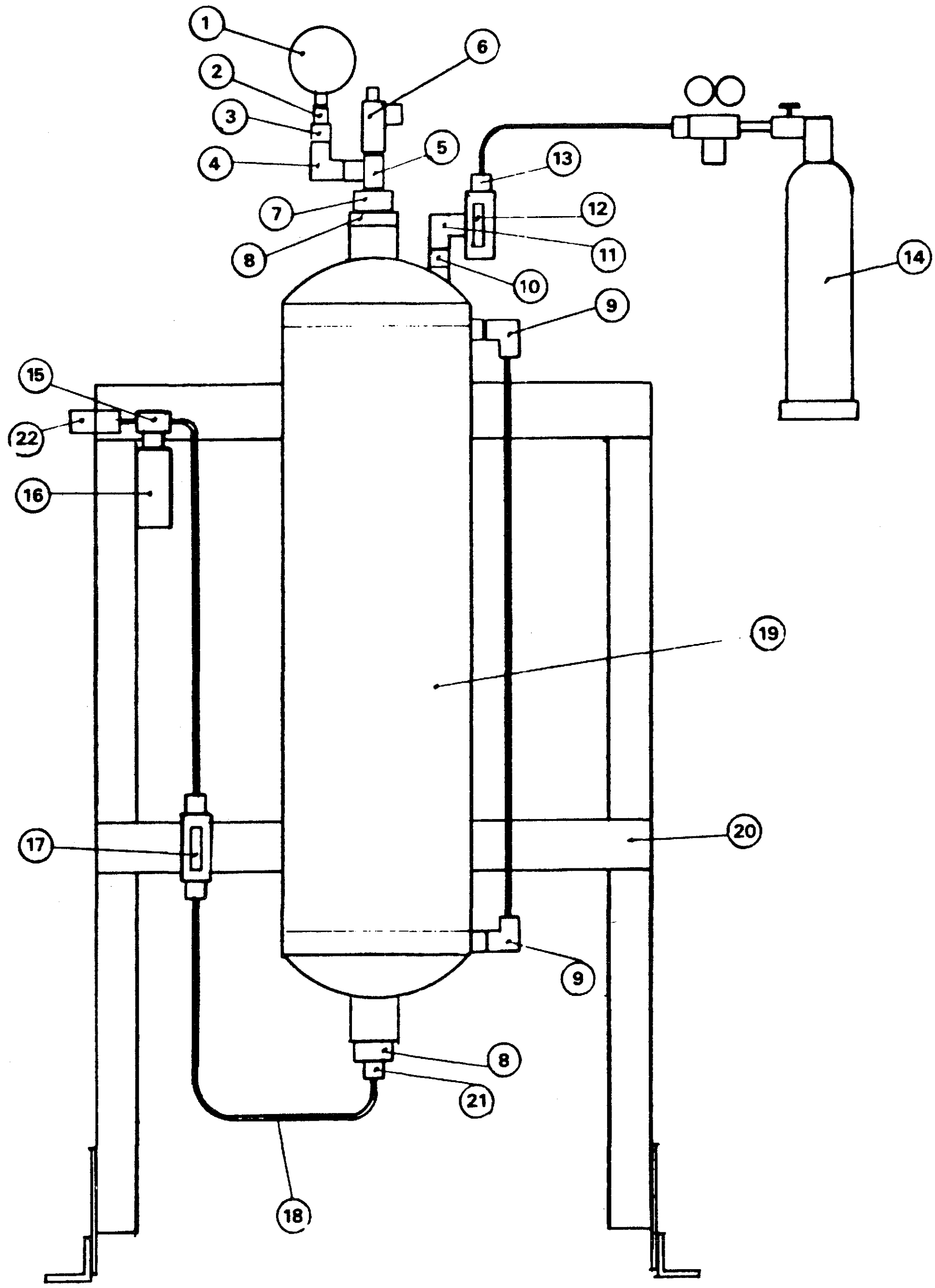
Two packers are separated by rods and can form a section from 1 m. to 20 m. or larger. The bottom packer, furthest into the borehole, is a standard unit produced by Petrometalic with a rubber element 63mm. in external diameter, by 1.04 m. inflated length. The top packer uses the same type of element but on a mandrel (central steel tubing) designed by SGAB. This mandrel incorporates two cross-over pipe networks. One switches water from inside the rods, from the mine pumps, to inside the test section. The other allows water in the straddle pipe, connected directly to the borehole below the bottom packer, to flow into the borehole above the top packer. This forms the rest-of-borehole zone. Another pipe through the packer joins the test zone to the pressure transducer which is attached by a union connector. This transducer, and the various pipe fittings, are protected by a steel sheath against abrasion damage.

The end of each packer contains an inflation port fitted with a compression joint. Both packers are inflated together through 6 mm. external and 3 mm. internal diameter plastic tubing. A short length joins the two packers, across the straddle, and a 250 m. length (inflation line) allows inflation from the mine area. The tubing, in the mine area, is stored on drums for ease of use.

2.3.2.4 Packer inflation equipment

This comprises a 30 litre capacity stainless steel reservoir, shaped like an aqualung tank, located on a free standing steel frame, as shown in figure 9. At the top of the tank there are two ports. The first has a dial pressure gauge (70 Bar) and a pressure relief valve. This is set to open at 40 Bar and protects the packers against over-inflation. The second port is fitted with a manual three-way shut-in valve. One way is connected to a flexible plastic tube which leads to a cylinder of compressed gas and regulator. The regulator can be set to any pressure from 1 to 100 Bar and is used to control the inflation pressure. Once inflated the gas supply can be isolated using the shut-in valve. The other valve route allows the reservoir to be vented to atmosphere to deflate the packers. At the side of the reservoir there is a sight tube so that the internal fluid level can be easily observed. At the bottom of the tank is another port to which is attached, by flexible plastic tube, a manual valve and 70 Bar pressure transducer. This line is connected to the packer inflation line drum by a quick fit junction. This allows the drum to be rotated freely when the packer probe is moved in the borehole. All the pipe work and components are rated to 70 Bar safe working pressure.

In operation the reservoir is first filled with water, which is the main inflation medium. This is achieved by using a hand operated pump to inject into the tank through the compressed gas port, when the gas line has been disconnected. If the packer probe is out of hole the whole inflation line should be filled with water as well. When the tank is full the gas supply is reconnected and inflation can start. The gas regulator is set to provide about 25 Bar pressure and water is forced from the tank into the packers until they are fully inflated. During this period the pressure transducer records tank pressure and not the pressure at the packers. Only when they are fully inflated, and there is no further water movement, will the reading be correct.



Legend

1	Pressure gauge	12	Ball valve
2	Adapter	13	male connector
3	Reducing bush	14	Nitrogen tank
4	Pipe elbow	15	Union tee
5	Tee	16	Pressure transducer
6	Relief valve	17	Ball valve
7	Hex nipple	18	Tubing
8	Reducing bush	19	Compressed air tank
9	Male elbow	20	Steel stage
10	Adapter	21	Male connector
11	Male elbow	22	Quick-fit connector

Figure 9 Packer inflation equipment

2.3.2.5 Borehole capping assembly

Each of the array borholes has a permanent steel casing, with a flange, to which can be attached a capping assembly. This seals all the tubes and rods to allow the borehole to regain an environmental pressure during testing.

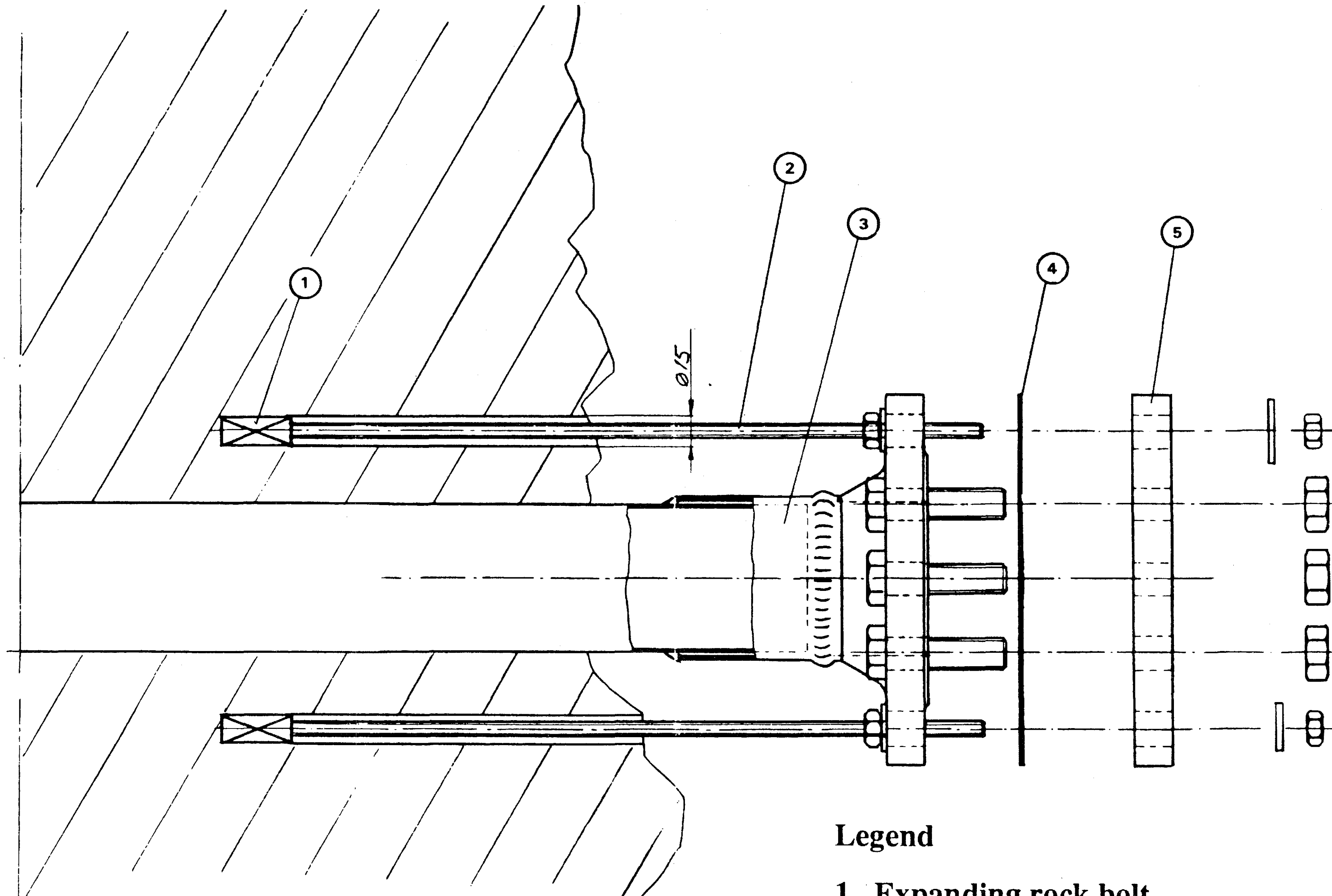
The permanent casing (figure 10) has an internal diameter of 70 mm. and is approximately 3 m. in length. This is sealed to the rock wall by a plastic resin compound injected into the annulus. A flange, with 10 symmetrical bolt holes, is welded to the casing. Two of these holes provide anchorage for "expanding-end", rock bolts which stop the casing from moving when the borehole is pressurised. Normally a steel plate is sealed to the flange by a cardboard gasket when the borehole is not being used as either the source or receiver.

The capping assembly, shown in figure 11, is essentially a very large compression fitting. The metal assembly casing is bolted onto the permanent casing prior to the installation of the source probe. The cone flares from an internal diameter of 75 mm. to 180 mm. to allow for the insertion of two identical rubber half cones. Each of these has semicircular notches cut in their flat faces designed to accommodate the rods, plastic tubes and electrical cables. The rubber elements are held in place by two 15 mm. thick semicircular steel plates which bolt onto the outside flange of the capping assembly case. When the bolts are tightened the plates compress the rubber elements which seal against the casing wall and the pipes.

The case has three threaded ports. The first is connected to the rest of borehole pump through the source board. The second allows access for a transducer, measuring the rest-of-borehole pressure, and the third provides a vent so that the borehole pressure can be released. This is important when opening the capping assembly to move the packer probe. The whole assembly is designed to operate safely to 40 Bar.

2.3.2.6 Water supply to the pumps

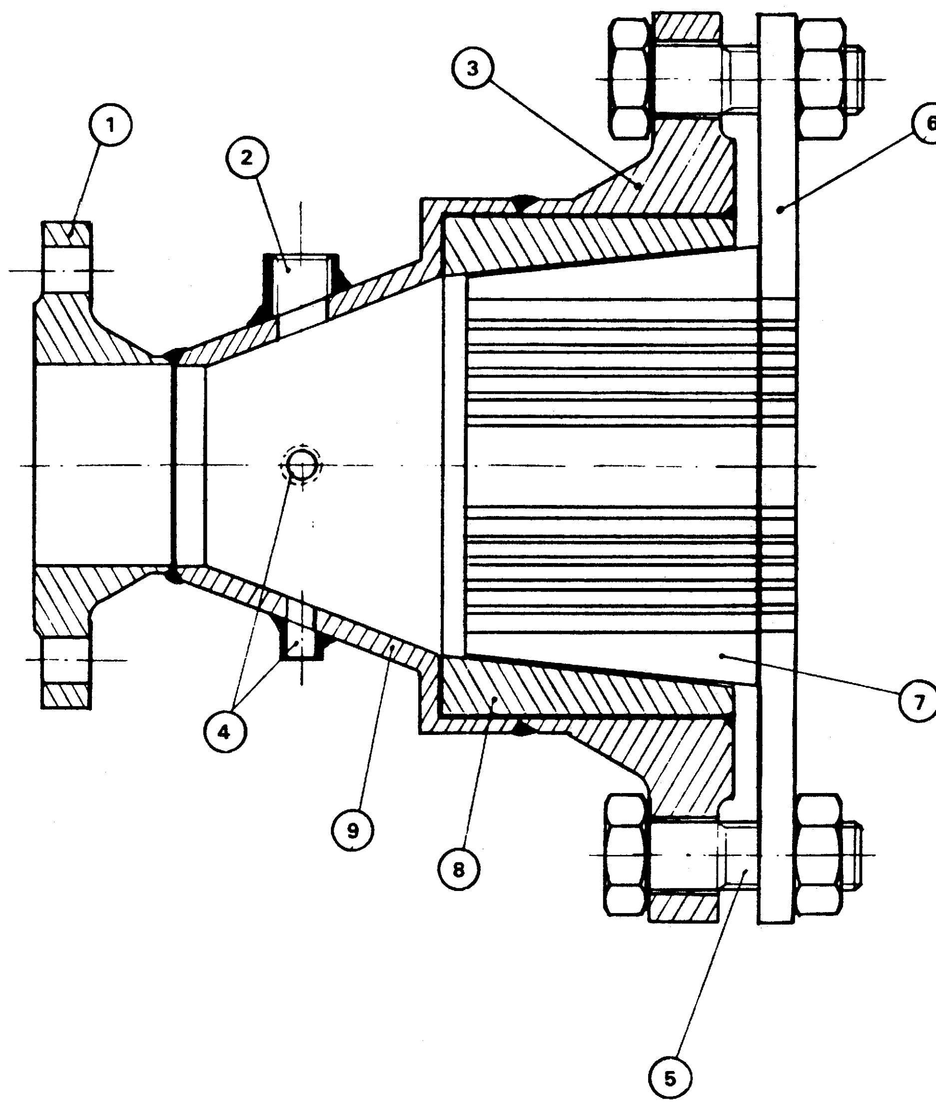
Both pumps are supplied by mine water piped to the working area from a reservoir on the 230 m. level. This is fed by mine drainage water. The piped water flows into a 250 litre capacity holding tank located in the roof of the working area some 6 m. above the pump inlets. An overflow runs out of the tank and down the wall of the mine so that the continuity of flow can be easily checked. This system reduces the high pressure of the piped supply to a more manageable value, provides a buffer supply in case of mains failure



Legend

1 Expanding rock bolt
2 Rock bolt arm
3 Steel casing weld
4 Cardboard gasket
5 Steel plate

Figure 10 **Permanent steel casing**



Legend

1 Flange with bolt holes
2 Port for rest-of borehole pump flow
3 Reinforced steel casing for bolt support
4 Threaded ports
5 Bolt, 1 of 10
6 Semi-circular steel clamping plate
7 Rubber sealing element
8 Inner steel sloped casing
9 Outer steel casing

Figure 11 **Capping assembly**

and allows the water to de-gas and drop any particulate sediment.

The supply system was modified during cross-hole testing. Borehole F6 has a water level some 33 m. below the mine area floor. This low environmental pressure results in a pressure field which is too low to allow the testing system to operate successfully. Therefore water is injected into F6, at a rate of 10 litres/minute, directly from the piped supply to raise the overall pressure to 10 m. above the mine floor level. Overflow water from F6 is fed to the tank and hence to the pumps.

2.3.2.7 Problems

In general all the equipment comprising the source survived the testing well. Some solenoid valves failed on the source board but these were easily replaced. The pumps caused more problems due to internal leakage but rate measurements kept the flow rate calibrated. One pump was sent away to have all its seals repaired when the internal leakage rate suddenly exceeded 125 cm^3/min.. The same pump also had to be repaired when its torsion spring broke. This spring is normally held inside an oil bath. However, water entered the bath and the spring rusted.

2.3.3 Receiver borehole equipment

This comprises all the components of the receiver borehole and includes the receiver board, the packer probe, inflation system, borehole capping assembly and reference pressure system.

2.3.3.1 Receiver board

This is a board of similar dimensions and design characteristics to the source board. It contains solenoids, steel pipe, a control panel, four pressure transducers and three display boxes. Connections are also provided for pulse testing and to the reference pressure tube.

On the left of the board there are seven access lines, one for each of the receiver zones. Each has a quick fit connector and a twin set of solenoid-actuated valves, under computer and manual control, to isolate or open a particular zone. All the lines merge into a manifold pipe in which the pressure is monitored by a 35 Bar transducer (zone pressure). A solenoid-actuated valve is fitted to the manifold pipe which, when opened, allows pressure to be vented. This is normally closed but when opened in conjunction with a zone solenoid causes the zone pressure to fall to initiate a pulse test. A manual valve provides a back-up to this "pulse solenoid valve".

On the right of the board is the reference pressure line minitored by the 35 Bar reference pressure transducer. Between the input and reference lines are the 7 and 1 Bar differential transducers but they are isolated by solenoid valve switching systems. Each Differential transducer has an identical group of solenoid valves comprising one three way (normally open) and one two way (normally closed) valves. Under non-measurement conditions the transducer is isolated from the zone pressure by the two way valve. Both sides of the transducer are connected to the reference pressure. During measurement the two valves are organised so that the reference pressure is on one side of the transducer and the zone pressure on the other.

The control box contains the power supply for the solenoid valves. On its face is a pictogram of the receiver board with manual push switches to operate all the solenoids. Light indicators show whether a valve is opened or close and whether by manual or computer control.

The board also contains three digital display units which show readings of pressure from the zone, reference and 7 Bar differential transducers. When power to the control and measurement system is cut these displays give false readings as they are fed by an analogue signal from the DPI-420.

2.3.3.2 Borehole packer probe

This comprises six packers which isolate seven sections in the receiver borehole. The packers are manufactured by SGAB using a commercial rubber element made by Ductube. Each has a deflated diameter of 67 mm. and inflated sealing length of 1.14 m.. The internal construction of each packer differs depending on its position in the probe. The lowest packer contains one inflation line and one zone sampling line, to measure the pressure in receiver zone 1. The highest packer has one inflation line and six sampling lines to measure the pressures in zones 1 to 6 inclusive. The single inflation line means that all the packers are inflated together.

The packers are physically separated into zones 2.4 m. long by threaded steel pipes. However, the spacing is easily varied. The inflation line and sampling lines are connected by short lengths of 6 mm. external diameter flexible plastic tubing. Compression fittings are used to make the connections. Lengths of similar tubing, 250 m.long, connect the probe to the working area in the mine. Each tube is stored on a reel which can be wound and unwound to feed tube into the borehole. Each reel has a quick fit connector so that the tube can be connected to the receiver board.

The total length of the probe is about 19 m. and it cannot be placed into or removed from a borehole as a single unit. Instead each packer must be handled separately so that the entire probe is actually assembled as it is inserted into the borehole.

2.3.3.3 Packer inflation equipment

This is identical to that used in the source borehole except that the reservoir tank holds twice the volume. This is required to ensure that the six packers are completely filled with water on inflation.

2.3.3.4 Borehole capping assembly

This is identical to that used on the source borehole. However the ports perform different functions. As no water is injected to the borehole the pump port is sealed. The pressure in the upper section of the hole, receiver zone 7, is not measured by a transducer on the assembly. Instead a 6 mm. plastic tube connects the pressure port to the correct line on the receiver board.

2.3.3.5 Reference pressure system

This is the equipment which supplies a back pressure to the differential pressure transducers. It is also used to generate heads during single hole slug and pulse tests. It comprises a 12 mm. external diameter (8 mm. internal diameter) extending 300 m. along the 360 m. level tunnel to a ventilation shaft up which the tubing continues to the surface. The water level in the tube can be raised or lowered, by injecting or abstracting fluid, to create the required pressure at the receiver board.

During the installation of the testing system in the mine a marked pressure fluctuation was noted on the reference line. The pressure varied by 0.25 m. over several seconds and was assumed to be due to the great length of tubing vibrating in the mine air currents. The amount of fluctuation was unacceptable if accurate differential pressures were to be measured. Therefore a "pressure filter" was located between the tubing and the receiver board.

The pressure filter, shown in figure 12, is similar to the equipment used to inflate the packers. The reservoir is not totally filled with water so that an air pocket is maintained at the top. A Tee piece is inserted in the sighting tube to provide a connection to the receiver board. All the tubing associated with the filter is of narrow diameter (6 by 3 mm.). The combination of gas compressibility and tube diameter changes reduces any pressure fluctuations to less than 0.01 m. over short time scales.

2.3.3.6 Problems

Some problems occur when measuring zone pressures using the receiver equipment. Firstly, the solenoid-actuated valves have a slight positive displacement of volume when they open and close, which can cause small pressure changes. The volume involved is small compared to the pipe volume and is equalised usually within 5 seconds. Secondly, small volumes of water can be transmitted between the reference pressure system and a receiver zone when the differential pressure transducers are accessed. The direction and rate of flow depends on the head difference. As the transducers are accessed in a regular manner, the water transference appears as a pressure drift, usually not exceeding one metre per day. The effect can be minimised by setting the reference pressure close to that in the receiver zones. A third problem is due to sequential zone pressure measurement. When each zone is accessed the pressure in the steel pipes between the zone solenoid valve and the measuring transducer is changed to that in the zone. When the zone valve closes the pressure in the steel pipe remains. If the next zone pressure differs from the first, its pressure must be equalised with that in the steel pipe. If the zone transmissivity is very low equilisation may not be possible on the time scale allowed for measurement and a false pressure will be recorded. Additionally a real pressure response to a sinusoid test, in a zone with a high transmissivity, may be transferred to zones with low value. Caution must be shown when picking out which are real and false responses. The problem could be overcome by standardising the pipe pressure between measurements to the reference pressure.

A small problem is caused by the length of the packer probe and the use of compression fittings for the pressure tubes. When removing the probe from a borehole all the fittings must be disconnected. This can be difficult in the confined space available and can lead to mistakes of connecting the wrong tube to a specific section. All plastic tubes should be

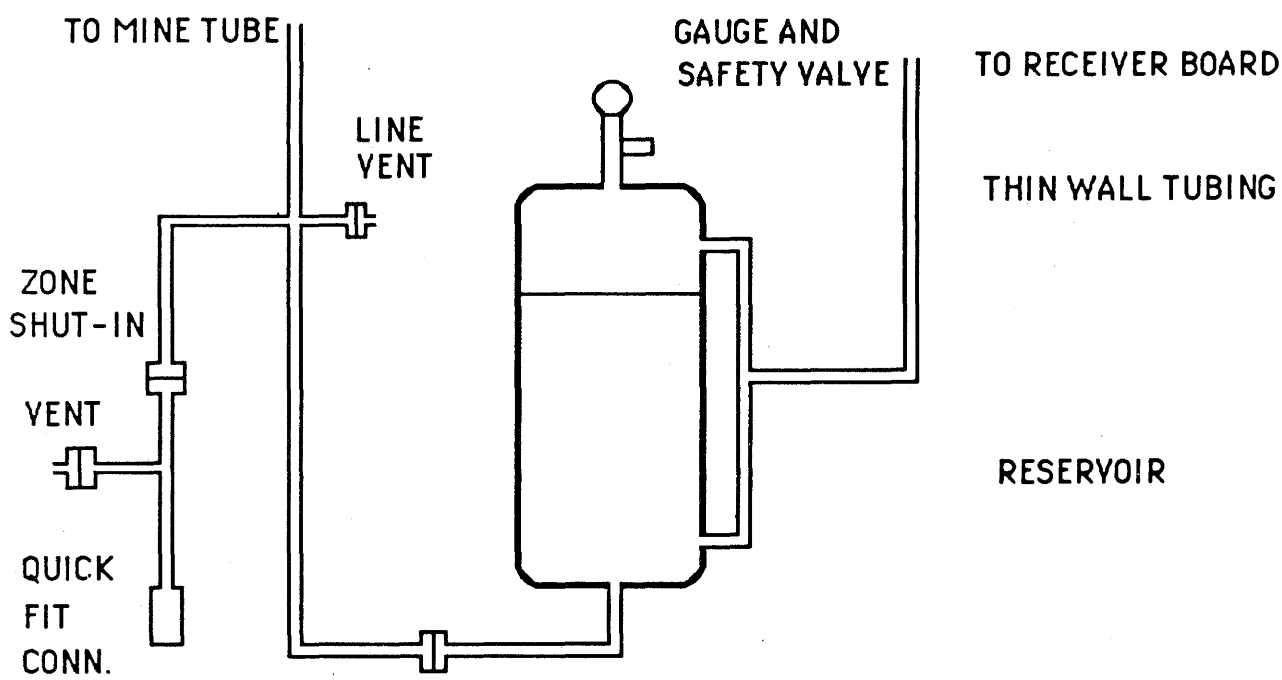


Figure 12 **Reference pressure system filter**

colour coded and push-fit connectors used instead of the compression fittings.

2.3.4 Miscellaneous equipment

This includes a hand operated hydraulic pump and fittings for the observation boreholes. The operators must also be supplied with a good set of tools and spare compression fittings, tubing and valves.

2.3.4.1 Hand operated pump

This is a small portable lever-actuated pump, with a built-in reservoir capable of generating flows of 0.5 litres/minute at pressures upto 40 Bar. It was intended to use the pump as an emergency replacement for the rest-of-borehole pump. This, fortunately, was never necesary. The pump is used for filling the packer inflation reservoir and the reference pressure system.

2.3.4.2 Observation boreholes

These are the boreholes in the array which do not contain either source or receiver probes. They are sealed by a steel plate bolted onto the permanent casing. Each plate has two threaded ports, one for a transducer and the other for a manual ball valve. The total borehole pressure is monitored during tests to determine if there are any major hydraulic connections.

3. PROGRAMS USED BY THE HYDRAULIC TESTING SYSTEM

The hydraulic testing system includes the equipment in the mine working area and a computer in the surface offices which is used for data processing. Programs exist for both installations.

3.1 Programs used by the mine equipment

All these programs are written in Pascal MT+ compiled from text produced on a Mince screen editing package. As the testing progressed some of the programs were modified to make them more user-friendly.

The limited capacity of the microcomputer (64K RAM working area) has necessitated the use of several sub-programs which can be loaded from disc to enable the system to operate. There are five sub-programs:-

FIXDEF-in which measured parameters can be selected, test type chosen and data files opened.
MEASURE- which performs the chosen test.
SHOWDATA- in which data collected by MEASURE, and stored to disc, can be retrieved and plotted to a matrix printer.
MINESURF- which alllows data to be transmitted by modem from the mine working area to the surface. At surface the data is stored on an ABC 800 microcomputer.
PULSE- This is a shortened version of MEASURE and can only perform transient (slug and pulse) tests.

To execute a test the FIXDEF program is first selected. The test type is chosen as are the parameters which are to be measured and stored. A data file is then opened to which is written the header data (date, time, measured points, operators name etc.). MEASURE is then called and uses a command file created by FIXDEF to perform the selected test. At the completion of the test SHOWDATA is used to display the results graphically or provide a print-out. Alternatively, the data can be sent to the surface for more detailed processing using MINESURF.

The structuring and operation of each of the sub-programs is explained in detail below.

3.1.1 FIXDEF

FIXDEF allows the operator to modify the command file used by the MEASURE program to perform a particular test. This command file comprises four sections, each of which can be called separately from a central menu.

1: Parameter selection. The testing system allows 35 pressures or flows to be scanned. These are listed in table 1. Various options are available for each or these parameters:-
a) USERNAME an operator changeable text name used to identify the parameter.
b) MEASURE whether the parameter is to be measured or not.
c) PLOT the parameter can be graphically plotted to the matrix printer if plot is selected. Ten parameters can be plotted during any test.
d) STORE enables a measured parameter to be stored to disc.

TABLE 1 COMMAND FILE PARAMETERS SET BY FIXDEF

NAME	FUNCTION
outside source section	pressure rest of source hole
source section	pressure in source section
receiver zones 1-7 absolute	pressure 35 bar
receiver zones 1-7 7 bar differential	pressure differential 7 bar
receiver zones 1-7 1 bar differential	pressure differential 1 bar
reference pressure	pressure in reference system
source packer pressure	pressure 0-70 bars
receiver packer pressure	pressure 0-70 bars
flow rate to source section	flow litres/minute
flow rate to outside source	flow litres/minute
volume to source section	cumulative volume litres
volume to outside source section	cumulative volume litres
observation boreholes 1-4	pressure 0-35 bars

e) PRINT the same as plot but a numerical rather than graphical output.

f) DISPLAY outputs to the monitor screen.

g) ALARM the operator may select a maximum and minimum value which, if alarm is active, causes a warning to be output to the screen. For example, source packer pressure may be alarm activated. If the pressure falls below the minimum value the operator is warned and can take suitable action.

h) CRITICAL ALARM the same as alarm except that the test is automatically and safely shut down. For example, a minimum source packer pressure value can be chosen at which the packers are no longer sealing. If the pressure falls below this value the test is terminated.

i) CHANNEL pressures are read from a transducer located on a specific channel on the DPI 420 peripheral. If the transducer is changed then the new calibrated channel number is entered using this option.

2: Test type selection. This component of the sub-program permits the operator not only to select the test type but also to set many of the control variables which will be used by MEASURE. The program asks simple questions which prompt the operator for replies.

A choice is made between the three test types which are available:

a) Periodical including square and sinusoidal wave forms. Constant tests (either pressure or flow, injection or abstraction) are performed using the square option.

b) Transient tests include pulse and slug tests.

c) Passive mode, during which there is no active water input or output, is selected for monitoring natural water pressure fluctuations.

If periodical testing has been selected, the operator may now choose the number of waves, wave period, amplitude (in Pascals) and whether the initial direction of change should be positive or negative. Each wave form can be chosen to be based on pressure or flow. The operator must also select the timing variables of the test such as the initial delay, the sample interval and the pump interrupt and control time.

3: Hole information. This section is used to enter header data to the command file which is supplementary to that provided by the username. The operator is prompted to enter information on the source borehole, receiver zones and observation boreholes. Specific depths and borehole and zone lengths can be entered together with a status-flag which indicates whether the zone is to be measured or not.

4: Open data file. Data collected during a test is stored to disc under a file name created in FIXDEF. A simple code is used in the name to identify the test type and whether it is single or cross hole. Information is stored to disc in string form with a header section giving test details followed by the real data. See appendix 1 for the structure of the file.

3.1.2 MEASURE

This is the sub-program which performs the test selected and specified in FIXDEF. During an active test this program controls the input and output of water to the source zone whilst monitoring the parameters requested by the operator and producing a visual display of the results. To achieve this MEASURE is composed of several inter-related parts which are described in general terms below and in greater detail in the appendices. A flow diagram of this program is presented in figure 13.

1) Operator initiation. The operator must identify the command and data file names when requested. Next, the program asks for two critcal parameters which control the rate at which the pumps change flow rate to produce the desired wave form. These are related to the transmissivity and storativity of the rock adjacent to the test zone, previously measured by a single borehole transient test. Finally, the operator selects the scaling factors for the graphical output of the matrix printer.

2) Pump initiation. Whilst the operator is entering the above information, the central

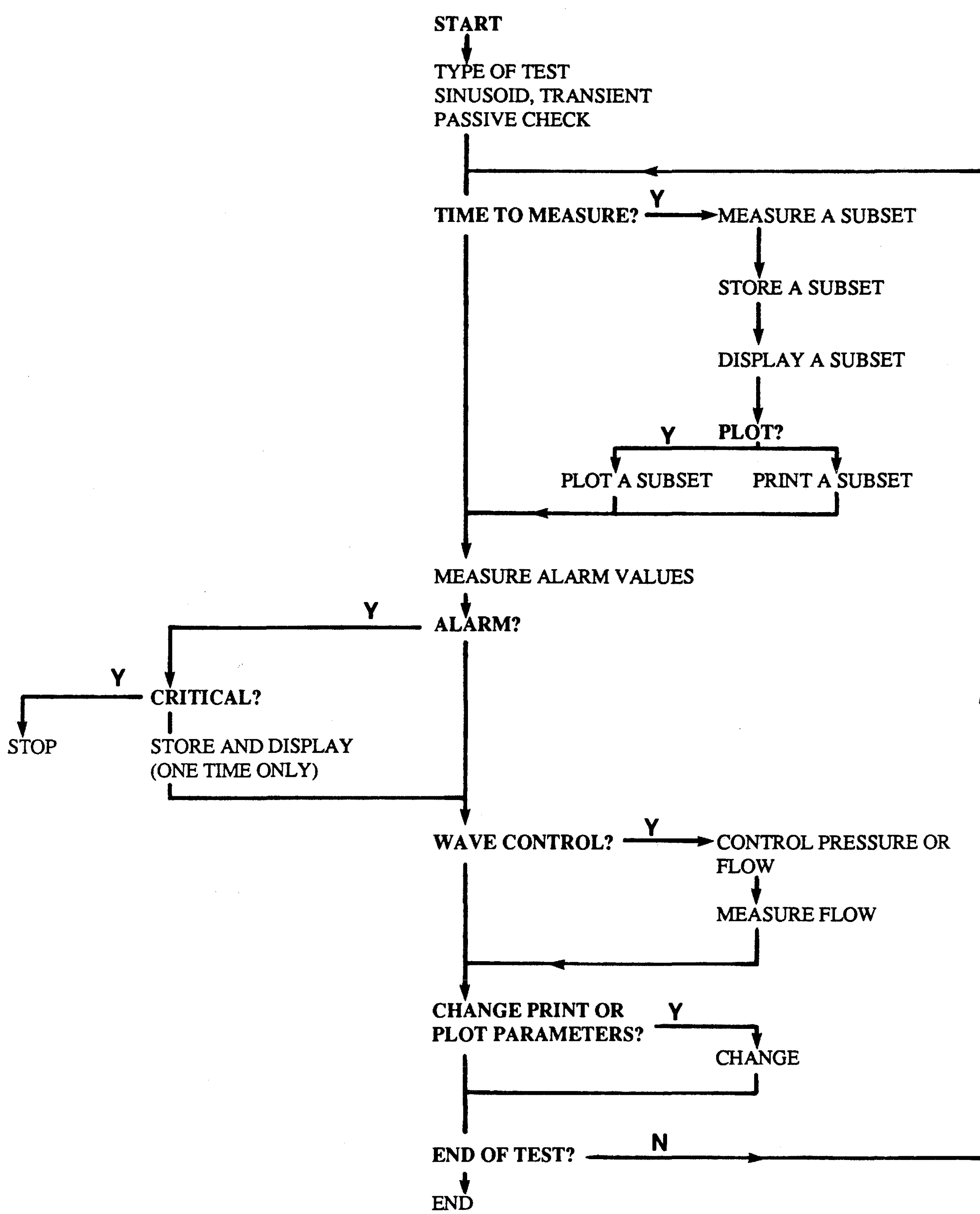


Figure 13 **Flow diagram of MEASURE program**

processor requests the pumps to find their starting points. The ram of each pump is moved to its right-side limit switch whilst isolated from the borehole, so there is no water transfer. All flow and volume variables are set to zero.

3) Test start. The operator starts the test from the keyboard which remains active throughout. Thus, it is possible to stop the test completely or stop water pumping whilst continuing to measure pressures (commands STOP and INJSTOP). The system proceeds to scan all the requested parameters during the initial time delay period. At the end of this the pumps are activated and cause the source zone pressures or flows to follow the selected pattern for the required number of periods. The pumps are then stopped but pressure measurements are continued until the test is stopped from the keyboard.

4) Pump control. A large component of the measure program is dedicated to controlling the two ram pumps, one for the source zone and the other for the rest of the borehole. During an active test the program causes the pumps to inject or abstract water from the source zone according to the pattern set by the operator. Every ten seconds the program calculates the pressure or flow which should be occurring in the source section. This value is then compared with the measured value and the pump flow rate and direction are changed accordingly. The rate at which the change occurs is partly determined by the operator set parameters and partly by the program. The rate must never be so great as to cause an erratic hydrauic signal. The program always ensures a smooth rate of change. Additionally, various pumping rates, which may cause the cylinders to resonate, are automatically avoided.

Whilst the first pump is causing pressure fluctuations in the source zone, the measure program causes the second pump to maintain a constant pressure in the rest of the source borehole. Every ten seconds the rest of borehole pressure is measured and compared with either a pre-test measured or operator set value. If a difference is apparent then water is either injected or abstracted to maintain the initial pressure. Thus any leakage of hydraulic signal to the rest of the source borehole is damped out.

Both the pumps are operated by stepping-motor positioned hydraulic rams. The detailed operation of each pump is controlled by a dedicated microprocessor with its own program. The MEASURE program can interogate each of these for positional data which are totalled up to yield flow rates and cumulated as flow volumes. See appendix 2 which describes pump control in greater detail.

3.1.3 SHOWDATA. This program allows an operator to select up to ten parameters, measured and stored to disc by MEASURE, and plot them on a matrix printer. The program requests a data file name and then lists the parameters which have been stored. The operator can display selected ones to the screen to examine the values. Different axis ranges can be set for each parameter prior to plotting the data.

3.1.4 MINESURF. This program can be called to transmit data stored on disc, via a serial port, to a telephone modem. The baud rate is 1200, 8 bits/character, no parity check and 2 stop bits. The first transmitted string is START followed by the file name. At the end of data transfer the string STOP is sent.

3.1.5 PULSE. This is simply a modified version of the MEASURE program in which many of the options have been removed so that it can only perform transient tests (pulse and slug). FIXDEF need not be called as PULSE contains menu inputs for opening file names etc..

3.2 Programs used in the mine offices

The mine offices house an ABC 800 microcomputer linked to a matrix printer and pen plotter. Programs written in Basic for this machine are used to process information collected in the mine and transmitted to the surface. The following programs are available.

3.2.1 SURFMINE

This allows the computer to accept strings sent by MINESURF, via a modem, and store them to disc. This provides a copy of the data for use by the other programs. Master copies of the data discs are also made to protect against data loss.

3.3.2 SINE2

This is a menu controlled program which is interactive with the operator and allows data to be entered from disc, to be processed and output to a plotter. Its primary use is to compare sinusoidal waves from the source zone and a receiver section to calculate phase lag and amplitude drop. The limited size of the computer and the large volume of data necessitates chaining between six sub-programs of which SINE2 is the master.

The operator enters the name of the file he wishes to process. The program scans the header and early data, between the first time markers, stored in the file and presents a list of usernames. The operator selects two of these. The program then searches each record of the data file to locate strings which contain the selected usernames. These strings are stripped to remove the numeric information. Real scan times are converted to minutes since the test started and pressures are converted from Pascals to Bar. These are stored to arrays. When the process is finished the central menu is displayed.

The two curves can now be plotted on the colour monitor. The program searches the arrays for the smallest and largest values and auto-scales the plot. A hard copy can be reproduced on the pen plotter. The data can also be printed on the screen or to the printer. An option is available for correcting the curves for drift. This is extremely useful for data collected on a rising or falling pressure limb.

The sine fitting sub-program allows the operator to select parts of the data set. It performs drift corrections of the source and receiver signals and does a least squares fit of each to a sinusoid of period equal to the period of the test. From this is calculated the amplitude and phase shift of the receiver relative to the source. The data and best fit curves can be plotted to screen and to the pen plotter. Additionally a listing of all the test parameters and results can be made to the matrix printer.

An option is provided to process flow information which scans the data for maximum and minimum flow rates. The use of this program for interpretation is described in Black *et al* (1986).

3.2.3 PULSE

This program performs many of the data handling fuctions of SINE2 except that it analyses slug and pulse tests. Once the data is stored to arrays it is put into the standard format, that is arithmetic head at time t divided by initial head change plotted against log time since head change. This is plotted to the screen. At this stage it is possible to correct the data for any pressure drift. The operator can now select either automatic or manual processing. In automatic mode the data is compared to type curves held as arrays in the computer memory. A least squares approach is used to find the curve with the best fit. When the effective tubing radius, used during the test, is entered by the operator the program calculates the zone transmissivity and storativity. This is printed out as hard copy together with the test parameters. A plot of the data and type curve can be produced by the pen plotter. In manual mode the operator enters type curve characteristics which the program then compares with the data. The degree of fit and hydraulic conductivity of the zone are produced.

3.2.4 CHOLEPRO

(Cross HOLE PROcessing). This is a general processing program which can input the data from a single username and present the results graphically. It is used for presenting information from constant rate or constant head tests.

3.2.5 Utility programs

Various small programs exist for examining the contents of data files, rewriting header data and printing files.

4.0 PROCEDURES FOR HYDRAULIC TESTING

4.1 Introduction

In this section details are provided on how the equipment is used to perform hydraulic tests of the following types;

1) Pulse and slug tests
2) Constant rate and constant head tests
3) Sinusoidal and square wave tests
4) Passive tests.

Some methods of using the equipment, such as packer inflation and rod handling, are common to all the test types and these are described first to avoid repetition. The detailed hydraulic test procedures are presented in detail later.

4.2 Common procedures

The following procedures such as rod handling, inflating packers and record keeping are used in all the different test types.

4.2.1 Rod handling and positioning packers

Both the source and receiver packer strings are located in the boreholes by rigid rods. These are manufactured from aluminium, to make them as light as reasonably possible, have an internal diameter of 20 mm., an external diameter of 33 mm. and are 3 m. in length. Each has parallel threads made from stainless steel to minimise wear. As the rods transmit fluid to the source zone during testing each joint is sealed by a rubber O-ring. These should be checked regularily for damage and changed if necessary as very small leaks can cause large errors in the results.

The rods are also used to measure the distance that the packers are located in the boreholes. Thus great care is be taken when adding and removing rods from the string to ensure that the positioning is accurate. The beginning of borehole casing was always used as the datum.

Flexible plastic tubing and electrical leads are anchored to the rods every 6 m. using water proof adhesive tape. This stops the tubes becoming entangled and damaged during removal from the borehole.

Pushing the rods into and pulling them from the holes is achieved using a hydraulically powered ram (stroke 1.05 m.) fitted with automatically actuated rod clamps of a size suitable to the rod diameter. This is aligned with the borehole using a "spider frame" attached by rock bolts to the mine wall at one end and supported by telescopic legs at the other end. The ram is quite heavy and the alignment proved difficult until an overhead crane was installed. Once positioned the ram is moved in and out by manipulating levers and is very simple to operate.

4.2.2 Sealing the packers to maintain pressure

The source and receiver boreholes are sealed using a cone compression device to stop water flowing into the mine and, hence, reducing the overall pressure in the rock. The two rubber sealing elements must be checked for damage and inserted carefully into the metal cone to avoid the introduction of particulate material. Plastic tubes and cables must fit well into the access slots so as not to override them. Any slots not used by down-hole cables must be blocked using short "blind" tubes. The steel retaining plates are then lifted into place and bolted on. The bolts are tightened so that the plates apply an even pressure to the rubber elements to acheive a good seal.

Boreholes which do not contain packer strings are sealed with a simple steel plate and gasket. Over time the metal sealing surfaces of these became rusted and required cleaning with a wire brush.

4.2.3 Inflation of packers

Similar procedures are used when inflating both the source and receiver packers. Both systems have a reservoir connected to a regulated compressed gas supply. The reservoir should contain enough water to totally fill the packers when inflated.

Packer inflation can cause a rapid rise in pressure in the zone between the packers which can take a considerable time to dissipate. Therefore, zones must be connected to a large volume of water or water and air so that the pressure fluctuations are reduced. In the source borehole system the plastic tube linking the rods to the source pump is disconnected and reconnected to the reference pressure tube. A valve is opened to allow the pressures to equalise to that in the sealed total borehole.

The compressed gas supply is turned on to inflate the packers to a pressure of about 30 Bar, which can take up to 10 minutes. Monitoring the pressure of the test section shows the sudden pressure rise and decline that indicates that the packers have sealed against the borehole walls. After inflation the test section is reconnected to the source pump unless a pulse or slug test is envisaged.

Before inflating the receiver packers the zones are connected together by manually opening the zone-access solenoids on the receiver board. This equalises the pressure between the test zones and allows excess water to escape into one of the long receiver sections. The "pulse valve", on the receiver board, is opened to allow any gas in the narrow diameter tubes to escape. The valve is closed when the tubes are totally filled with water. Any gas would increase the compressibility and increase zone response times. Inflation can take upto 30 minutes. The solenoid actuated valves are then manually selected to isolate each of the sections.

4.2.4 Manual monitoring

Although the testing system is automated, various components require to be checked during a test to ensure that it is operating correctly. Faults can be detected which may be serious enough to cause a test to be aborted. Alternatively, they may not be critical and can be repaired during general maintenance.

The pumps must have a supply of water to avoid damage to the sealing rings. The tank over-flow can be checked to ensure that the pressure feed is still operating.

Various quick-fit connectors and associated plastic tubing, especially those involved in packer inflation, should be checked for leaks.

Pressure gauges on the inflation reservoirs, source and receiver boards can be read and the readings compared with the transducer outputs to verify that they are operating correctly.

Both the receiver and source boards rely on the operation of electric solenoids to switch water flows and pressures. These tend to overheat before failure which can be checked by touch or looking for a slight blackening of the plastic casing. Rapid replacement is advised. Examining the transducer readout pattern, presented on the computer printer, can reveal the total failure of a solenoid.

4.2.5 Record keeping

Hydraulic testing, both single and cross hole, generates a large number of individual tests. In order to rapidly track down any one result it is necessary to maintain a detailed set of paper records. Test information is stored as a header with each file on the magnetic discs. However, this is not readily accessible. File names are created and coded to provide information on the test type, which boreholes are involved and the depths of packers. A record of each file name is kept in a test log book together with the date. Additionally, a standard test sheet is filled out which records the following;

a) The file number and date
b) Depths of packers in the source borehole and name of hole

c) The same as b) for the receiver borehole

d) The type of test and the reason for performing it

e) Information on the frequency, amplitude and periods for sinusoid tests

f) The scan interval

g) Various details of equipment performance, such as packer pressures and computer acquisition problems.

4.3 Testing procedures

4.3.1 Slug and pulse testing in single boreholes

Both tests are similar in that the response to an instantaneous change in zone pressure is analysed to determine transmissivity and storage of the rock mass. In the pulse test, the pressure change is due to the compressibility of water within the test zone that is "shut in", plus the compliance of the packers, tubing and valves. The slug test differs in that the pressure change is due to a water level fluctuation in a tube of fixed internal radius. Smaller volumes of water are involved in pulse tests so that they are more rapid to execute but investigate the hydraulic properties of a smaller volume of rock around the borehole.

The testing system was not designed initially to perform slug tests as detailed single hole testing was not part of the original cross-hole programme. However, when the need arose the system was sufficiently adaptable so that modifications could easily be made to both equipment and procedures. The tests can be performed totally under automatic computer control. This requires that water is transmitted through the source board and that solenoids isolate various parts of the system. However, it soon became apparent that air pockets trapped in the extensive pipe work of the board were influencing the results. Trapped air changes the compressibility of fluid involved in pulse tests and as the volume of gas is variable the influence is not consistent. Therefore, the pipe connections were simplified and manual operation of valves was used, under directions from the computer which then made all the pressure measurements. Pulse testing in the receiver borehole, to determine zone response times, is fully under computer control.

In both tests the reference pressure system, normally used to provide a back pressure for the differential transducers on the receiver board, is utilised to create a pressure change in the test section. The following procedure is followed.

a) The packer string is inserted into the borehole so that the packers straddle the zone of interest. The borehole is re-sealed using the cone compression fitting and the rods are connected to the reference pressure system by a flexible plastic tube. The zone shut-in valve is closed.

b) The borehole pressure, which fell to atmospheric when the string was moved, is allowed to build up towards equilibrium. This may take up to half an hour or longer depending on how long the borehole was open. During this period the line vent valve on the back pressure system is opened to allow the escape of any entrapped air.

c) When the borehole pressure is close to equilibrium the water level in the reference pressure tube is adjusted so that it is close to that in the borehole. This is best achieved by opening the zone shut-in valve so that the borehole automatically fills or empties the tube to the correct level. Notes are made of the rest of hole and zone pressures.

d) The packers are inflated with the zone shut-in valve still open. During inflation the control computer is activated and PULSE is used to enter the required data for the test parameters. The zone pressure is monitored usually 7 times per log time period and the delay before the first reading is set to 5 seconds. This latter parameter allows any fluctuations caused when the valves are opened to die away so that a stable start-pressure results.

e) When the packers are fully inflated the zone shut-in valve is closed. This isolates the zone from the reference pressure tube so that a zone equilibrium pressure can be attained more rapidly. The zone pressure is allowed to develop. During this period the rest of hole and zone pressures are observed. Usually a difference develops indicating that the packers are sealing well to the borehole walls. If no difference develops it indicates either that the zone and total borehole pressures are equal or that there is a leak. A leak can be detected by lowering the rest-of-borehole pressure, by opening the valve on the cone compression borehole seal, whilst observing the zone pressure. If the latter falls rapidly there is a leak either around the packers or in the rod string. In the former case the packers can be inflated to a higher pressure or relocated slightly in the borehole. Leakage through the rods requires that the rod string is removed from the borehole and thoroughly checked.

f) If the packers are sealed correctly the zone pressure is allowed to develop until it approaches equilibrium. Pulse or slug tests performed on a violently changing base pressure are difficult to analyse and have inherent errors. When the operator is satisfied with the initial head then testing can begin.

g) The water level in the reference pressure system is adjusted to a value which is some 10 metres below that of the zone pressure. Water is either pumped into or out of the tube and the pressure allowed to stabilise. The test is started on the computer and the operator stands by to manipulate the zone shut-in valve. The computer activates a solenoid light on the source board to indicate that the valve should be opened. If a pulse test is required this valve is closed when the light is extinquished. In a slug test the valve is left open. Once initiated the test continues under computer control until it is terminated by the operator. This usually occurs after 90% of the imposed pressure has dissipated.

h) At the end of the test the data is sent to the surface computer, using a modem, for detailed analysis. Test results are usually sent in batches of six.

A slightly different technique is used to perform pulse tests on the receiver zones. Slug tests are impracticable due to the narrow diameter of the tubes connecting the zones to the mine cavity creating high friction loses. The procedure is as follows.

a) The packers are positioned in the borehole and inflated. When fully inflated the isolating solenoids on the receiver board are closed. Sufficient time is allowed for equilibrim zone pressures to develop.

b) Each receiver zone is tested separately so that individual computer files are created for every test. The receiver board pulse test line is connected to the zone shut-in valve which is opened. A separate valve is included on the receiver board which, under computer control, carries out the function of the manual valves.

c) The reference pressure system tube water level is adjusted to a value some 10 metres below the zone pressure. The test is started on the computer and allowed to proceed until stopped by the operator.

4.3.2 Constant rate and constant head tests

In constant rate testing water is either injected into or abstracted from the test zone at a fixed and constant flow rate. The change in pressure, either in the source zone or in adjacent receiver zones, is measured to yield the hydraulic properties of the rock mass. In a constant head test the pressure in the test zone is maintained at a constant value whilst changes in the flow rates are monitored.

Ideally the change in either flow or pressure should be applied instantaneously to the test section. The testing system is designed to produce changes over a set period of time rather than instantaneously. This is because the pumps need to approach a final flow or pressure at a preset rate to avoid possible damage through over-pressurisation of the system. Thus early time data from these tests, usually up to several minutes, tends to be distorted. This makes it difficult to detect such features as well bore storage and skin effect which influence the data at early time. "Late-time" data is more suitable for analysis. Recovery data can also be analysed.

The constant rate and head tests were used in two separate modes during the field testing at Stripa. Firstly in single boreholes the tests were used in zones which had high hydraulic conductivities. In such zones the flow rate was too high to perform a slug test and the result was affected by friction in the pipe work. Secondly, they were used in cross-hole mode for a direct comparison with sinusoidal tests.

There is no section of the FIXDEF and MEASURE programmes specifically dedicated to performing constant rate and head tests. Instead the versatility of the programmes is exploited. This, however, does require some careful thought by the operator to achieve a successful result. Both tests are set up using the square wave option in FIXDEF. This option requires that the time for one square wave is input. The constant tests are contolled by the first part of the wave so that the operator must select a value which provides adequate time for test completion. The test is terminated by the operator, usually using INJSTOP, which stops the pumps but proceeds to gather pressure data on the recovery. Additionally, in constant rate tests, the operator must input a value for the flow rate. This must be selected with great care and related to any previously measured value of hydraulic conductivity. If too high a value is chosen the source zone may overpressurise, causing damage to the packers and tubing. Therefore an alarm and critical alarm must be set on the source pressure. Under these alarm conditions the tests will be automatically aborted if the pressures reach dangerous levels.

Once the operator is satisfied that sufficient thought has been applied to the tests problem the following procedure is used.

a) The packers of the source zone, and those of the receiver, if a cross-hole test is envisaged, are positioned in the borehole and inflated, as previously described. After an equilibrium pressure for the source zone has been established, the flexible tube linking the source zone to the reference pressure system is reconnected to the source board. This causes a slight pressure disturbance which is quickly dissipated if the source zone has a high hydraulic conductivity.

b) FIXDEF is used to set the various test parameters taking particular notice of test length and flow rates, if it is a constant rate test. Alarm values are selected. The information is also entered onto the paper file.

c) The test is started using MEASURE. If pressures are still equilibrating then a delay of several hours can be stipulated before the active part of the test commences. It is suggested that the operator is present during the early stages of a constant rate test so that if the test is aborted, it can be restarted with a minium of lost time.

d) Testing is continued until the operator is satisfied that sufficient data has been collected. In a constant rate test this implies that the zone pressure has attained a steady value or is increasing very slowly. In a constant head test the flow rate should be steady. At this point the pumps are stopped, using the INJECT option, so that recovery data can be collected. During this phase general manual monitoring should be performed.

e) When pressures have recovered sufficiently to approach their starting values, the test is finally stopped. The data can then be transmitted to the surface for detailed analysis.

A slightly modified procedure was used when single hole testing in parts of the F6 borehole. Some zones have an environmental pressure (rest water level) which is below the level of the mine testing area. The total borehole rest water level is some 33 metres below the 360 metre floor. As the system was not designed to operate under such pressure conditions a method had to be improvised in the mine from the equipment available. In such zones, therefore, it was considered beneficial to use a manual testing system based on a simple reservoir to provide a test head.

The reservoir system comprises a flexible tube, connected to the rod string, a shut-in valve and a reservoir of known radius with a side, sighting tube to show the water level. This is marked with a notch 10 cms. down from the top. The normal procedures for packer inflation are followed until they are fully installed. The reservoir system is then fitted to the rod string and the shut-in valve is closed so that a test zone equilibrium pressure can be measured. The reservoir is filled with water. FIXDEF is called and set up for passive testing of the source zone, taking a zone pressure every 30 seconds. Measurement is started from MEASURE and a period of equilibrium pressures are recorded. Then the shut-in valve is opened to connect the reservoir with the source zone. The water level in the reservoir falls as water is injected into the rock. When the level falls to the notch the reservoir is replenished manually. The flow rate is recorded as the time required for the level to fall from the top of the reservoir to the notch. When the flow rate is unchanging the shut-in valve is closed and the recovery is monitored. Flow rates are written onto the print out produced during the test.

4.3.3 Sinusoidal testing

Sinusoidal testing is only used as a means of determining hydraulic properties between boreholes, creating the signal in the source zone and monitoring the response, to receiver sections, in another borehole. A full testing sequence comprises several tests at different frequencies. Usually 12 hour, 4 hour and 40 minute periods were used, with occasionally a 10 minute period in very transmissive zones. The system can produce either sinusoidal flow rate or sinusoidal pressure. In most tests only the pressure was controlled as this produced a better form of curve.

Each separate sinusoidal test comprises three phases, the length of each being set by the operator. Firstly there is a monitoring phase, usually no more than 4 hours during which ambient pressure changes can be recorded. Secondly there is the active phase in which the source zone and rest of borehole pressures are manipuleted by the pumps. Three or more sinusoidal periods may be included in this phase. Lastly there is another passive phase for monitoring ambient pressure changes. The passive phases are important to record pressure changes generated by sealing and unsealing boreholes in the array.

Both the sinusoidal test and the testing system are complicated so that the operator must be extremely careful when setting parameters in FIXDEF and MEASURE if a test result is to be satisfactory. Some of the important parameters are listed below.

i) Test pressure.
During the test the pressure is fluctuated above and below the environmental pressure of the source zone. Care must be taken that pressures do not rise too high or fall below atmospheric. Usually a value of plus and minur 1 Bar was selected. However, if the zone

is very transmissive the equipment may not be able to provide a sufficiently high flow rate. Under these circumstances the test pressure should be lowered to 0.5 Bar or even lower.

ii) Pump control parameters.

The rate at which the pumps can increase the rate at which they pump is set by two parameters provided by the operator. Since the generated hydraulic signal should closely follow the predicted curve these parameter values must be selected with care. The integrating constant can be varied between $1x10^{-7}$ and $1x10^{-5}$. The lower value is used in zones with a transmissivity of less than $1x10^{-10}m^2s^{-1}$ and the upper value in zones which exceed $1x10^{-7}m^2s^{-1}$. Values in between are proportional to the hydraulic transmissivity. The pump proportional control is set to 0.99 for most tests. If the pump constants are set incorrectly it is possible that the pumps can inject into the source zone at far too high a rate. This will result in very high source pressures and consequent damage to the equipment. Alarms can be set on the source zone pressure so that such an event can be avoided by aborting the test.

Separate pumps are provided for the source zone and the rest of borehole section. Often the rest of borehole transmissivity exceeds that of the source zone and higher control parameters must be selected for that pump. This is especially the case when some of the array boreholes are connected to the rest-of-borehole section. This was found to be necessary when testing some of the more transmissive zones. Signals produced in the source borehole caused the pressure of complete boreholes to fluctuate so that the source of any received signals was no longer well defined. Connecting boreholes to the rest-of-borehole zone allowed the fluctuations to be controlled.

iii) Valve delay constant and sampling interval.

The receiver board transducers are connected to one of the receiver zones by solenoid actuated valves as part of the measuring sequence. Each valve needs to be open for a period of time to allow pressure equilisation within the board pipework. Usually this takes up to 5 seconds. If a zone has a low transmissivity it may take far longer. The valve delay constant can be set by the operator to ensure that equalisation will occur. However, the time between full data scans, the sampling interval, cannot be too great otherwise important data might be lost. If all the receiver zones are measured with all 3 transducers and a delay of 5 seconds then a full scan will take over 2 minutes. If the sinusoid period is 1 hour then there will be 30 sample points per period. In selecting a valve delay the operator must calculate how many data points are required per period and the number of zones to be measured. At very short periods, of 20 minutes or less, it is only possible to measure one or two receiver zones during one test if a short sampling interval is required.

When the operator has considered the various aspects mentioned above the following procedure is used.

a) The source and receiver zone packers are positioned and inflated. Slug or pulse tests may be performed to determine the source and receiver zone transmissivities. The source zone is disconnected from the reference pressure system and connected to the source board.

b) Note is made of the receiver zone pressures and the reference pressure system is adjusted to a suitable value so that the 7 and 1 Bar differential transducers can operate. If the range of pressures is large this may not be possible. The operator must then select a back pressure which will allow the zones of most interest to be measured.

c) The test parameters are set using the FIXDEF programme paying regard to imposed pressure, pump constants and valve delay. The paper file is updated for the new test.

d) MEASURE is loaded into the computer and the test is started. If possible the operator should stay with the equipment during the initial cycle to ensure that the pumps are running correctly. Incorrect pump constants will become apparent at this time. Manual monitoring is performed notably watching the pump water supply.

e) When all the periods of sinusoidal fluctuation have been executed the test is stopped by the operator. In some instances, for example if no signal is received after 1 1/2 cycles, a test may be aborted early. The data file is sent to the surface for analysis.

4.3.5 Passive testing

This mode is used to collect data when the source zone pressure is not being manipulated. The pumps are not required and can be switched off. Any fluctuations may be due to natural causes, such as rainfall responses, or activities within the mine. The passive mode is also used in some testing as, for example, when a complete borehole is drained and the response is measured in the rest of the array boreholes.

The operator selects passive from the FIXDEF menu on the computer and enters those points which are to be measured. Such parameters as flow rates and volumes need not be measured and should be de-selected. This reduces the size of the data file which is stored to disc. MEASURE is loaded and the test started. When sufficient data has been collected the operator stops the test and the file can be transmitted to the surface.

5. DISCUSSION

The equipment, in its present form, can perform a variety of single and crosshole hydrogeological tests when operating in a mine environment. As the pumps are located outside the borehole, the environmental pressure of a test zone must be at least 1 Bar greater than atmospheric at the borehole cap if the system is to operate efficiently. Injection tests can be performed if the pressure is negative but the equipment is not ideally suited to this mode of operation. The equipment is rugged and designed to function with a minimum amount of interference from the operator while a test is in progress. This allows the operator more time to consider the possible implications of a particular test and to ensure that the results are valid.

The equipment can be used in any mine environment to characterise water movement. In addition to the type of work involved in the Stripa Phase II, it could be used to provide detailed information on hydraulic flow paths and environmental pressures prior to a tracer test. This would aid in the positioning of sampling and injection points and help in the tracer interpretation. The equipment could also be used to investigate the effect on groundwater flow of injection grouting of fractures by characterising the flow pattern before and after emplacement of the grout. This type of work would be applicable to problems outside radioactive waste disposal research. For example, in the fields of storage of gas and liquids underground in mined cavities and general mining where water flow needs to be reduced.

The equipment could also be modified to operate in boreholes drilled vertically from the surface, thus enabling the sinusoidal testing method to be used in sites prior to the construction of an underground cavity. In the source borehole, the water pumps would have to be placed in the borehole. A similar design of pump could be used for small flows and turbine pumps for higher flows. The receiver borehole equipment would also have to change to measure pressures directly in each isolated zone. However, the general logic of testing and many of the control functions would be identical to those of the existing system.

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7. REFERENCES

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APPENDIX 1

STORAGE OF TESTING DATA TO DISC FILES.

In FIXDEF the operator can create a file for permanent storage. FIXDEF writes header information to the file. Data is added to the file during MEASURE.

The header data comprises the following information.

i) Crosshole hydraulic test project. - This is the file identifier.

ii) USERNAME : (Connect status), Depth : ( ) , length : ( ) - This is the name of the source zone, whether it is connected, the depth, in metres, to the zone and the zone length.

iii) USERNAME : (Connect status), Depth : ( ) , length : ( ) - As above for the rest of borehole section.

iv) USERNAME : (Connect status), Depth : ( ) , length : ( ) - Receiver zone 1.

v) USERNAME : (Connect status), Depth : ( ) , length : ( ) - Receiver zone 2.

vi) USERNAME : (Connect status), Depth : ( ) , length : ( ) - Receiver zone 3.

vii) USERNAME : (Connect status), Depth : ( ) , length : ( ) - Receiver zone 4.

viii) USERNAME : (Connect status), Depth : ( ) , length : ( ) - Receiver zone 5.

ix) USERNAME : (Connect status), Depth : ( ) , length : ( ) - Receiver zone 6.

x) USERNAME : (Connect status), Depth : ( ) , length : ( ) - Receiver zone 7.

xi) Data file created : 00:00:00 00:00:00 - The date (year, month, day) and time (hour, minute, second) that the file was created.

xii) Scan time : 00:00:00 00:00:00 - The time between data scans.

xiii) Time for injection start : 00:00:00 00:00:00 - The time between starting the test and the pumps being activated.

xiv) Period time : 00:00:00 00:00:00 - The time for one sinusoid period.

xv) Signature : - Operator names or initials.

xvi) Test type : - Either periodical, pulse, or passive.

xvii) Variable regulated : - Either pressure or flow.

xviii) Shape of pulse : - Either sinusoid or square.

xix) Slope at start : - Either positive or negative. Positive indicates that the variable was increased at the test start.

xx) Transient section : USERNAME - The zone involved in a slug or pulse test.

xxi) Number of pulse periods : 0

xxii) Time between regulations : 0 - The time in seconds that the system adjusts pump rate during a test.

xxiii) Transient length : 0 - Time in seconds that the valve is opened to start a pulse test under automatic control.

xxiv) Transient to first scan : 0 - Time in seconds that the system waits before taking the first measurement in a pulse test once the shut-in valve has been closed.

xxv) Measurement/(time decade) : 0 - The number of data points collected per log time during a pulse test.

xxvi) Valve delay : 0 - The time in seconds that the receiver zone solenoid valves are opened before a pressure measurement is made.

xxvii) Max. amplitude (Pa or l/min) : 0 - The limit set by the operator for the maximum pressure (in Pascals) or flow rate that the system must attain in periodical tests.

xxviii) Start pressure, source (Pa) : 0 - The start pressure for the test. For flow rate this is normally zero.

xxix) Pressure outside source : 0 - The rest of hole starting pressure or flow rate.

xxx) First measurement made : 00:00:00 00:00:00 - The real time that the first measurement was made.

Data collected during MEASURE concerns the time that a scan started, the data and alarm triggers. Time is recorded as real time, from the computer clocks in the format,
T:000000000000 (yr, mon, day, hr,min,sec).
Data is recorded with a username and measurement in the format,
D:USERNAME; (value).
Alarms, which are only recorded on their first occurence, are formatted as
A:USERNAME; (value)

Thus a typical part of a file recording is a simple list of formatted strings of which the following is a short example.

T:850224101039
A:RECEIVER REFERENCE 35 BAR; 5.46000E+05
D:CALCPRESSURE; 0.00000E+00
D:F3/SOURCE 40-44; 6.09999E+05
T:850224101141
D:CALCPRESSURE; 0.00000E+00

APPENDIX 2

PUMP CONTROL

General Information.

The task of the program is to control the stepping motor speed to maintain a flow of from 0.03 ccs/min up to 3 litres/min with a maximun error of 10 percent. Usually the error is much better than the maximum.

Programs controlling the pumps are stored and run on microprocessors separate from the central CPU. Measure sends commands and recieves replies from these "stand alone" processors.

The pump control part of the MEASURE program is split into three parts. The dominant section is written in PASCAL MT/+ but two critical routines are in assemby language for speed of running. Both are invoked by hardware interupts.

The first (MOTINT) runs once for every stepping pulse sent to the stepping motor. The maximum rate is upto 1500 times per second requiring a maximum run time not exceeding 0.3 milliseconds. MOTINT controls the speed of the stepping motor and ensures that speed changes are smooth.

To get interupts at the correct intervals, three counters are connected in series and programmed with computed prescale and counter values. The first counter has the system clock (4MHz) as input and the last generates an interupt at zero count.

The other assembly routine is ALAINT which is invoked if one of the limit switches detects that the stepping motor has reached a position outside its normal operating range. Under these conditions ALAINT stops the stepping motor and ensures that it cannot be restarted without being re-initialised.

Control Algorithm.

The pump is run back and forth between two preset limits, 0 and 24000. 0 is at the right limit and 24000 at the extreme left. When a limit is reached, the input and output solenoid valves are switched and the motor is stopped and then restarted in the other direction. Note that this is unlike the case of a change in the flow sign ie changing from injecting to abstracting water for example.

This is caused by stopping the motor and restarting it in the other direction independant of its position on the linear scale and without switching the solenoid valves.

The pump flow may be in the range -30000 to +30000 corresponding to a real flows of -3 to +3 litres/minute. A flow value of 1 means that that the steping motor should be pulsed with a frequency of 0.05 Hz and 30000 corresponds to 1.5 kHz. At a frequency of 80 Hz the motor might go into resonance. This is simply avoided by setting the speed to the closest of either 75 or 85 Hz.

The speed range of the motor is very great and may not be changed from a maximum in one direction to a maximum in the other direction instantly, as this will damage the pump. Instead, the speed is decreased slowly and then increased in the other direction. Slowly means in the order of 100 milliseconds. This is acheived by separating the motor speeds (positive as well as negative) into classes (see later SETFLOW for details). A speed change is handled by allowing the speed to change in only one class at a time. If the required flow, as calculated within MEASURE, is within the same class then it is changed directly. However, if the new speed is in a different class, a default speed in the intermediate speed class is set and run for a while before it is changed to the final class.

After every change in speed class a preset number of steps have to be stepped before the speed is changed again.

Close to the limit where the motor is supposed to reverse direction, a "speed limit" mechanism is activated. Depending on the current speed, the current position is checked against the limit. If the present position is closer to the limit then can be allowed for in the present speed class, the speed is forced down progressively- exactly as when slowing the speed by selecting a lower flow rate-and not allowed to increase again until the motor has reversed. The speed limit mechanism overrides the normal speed control.

Hardware.

The program runs on a single board computer : "CPU80 Z80-ECB card" produced by Sentec data. This card contains a 4 MHz Z80 central processor unit, a Z80-PIO, a Z80-CTC and a Z80-SIO. The card can be configured with a maximum primary storage of 4 K EPROM and 2 K RAM.

Commands.

The main microcomputer controls the pump processors, and hence the pumps, through a sries of commands which are listed below. All the commands and replies are terminated by the ASCII characters <CR><LF>. Only capital letters are acccepted and the input is not echoed.

In the description below, "<value>" should be substituted by a signed integer in the real command, within the given range. A blank character is shown by the under score character "_".

Note that the "INIT" command must be given before the pump control program can become operative.

"INIT" This initialises the control program. The motor is positioned at the right limit of operation. A delay of at least one minute must follow this command before another can be accepted.

"FLOW_<value>" Sets the flow rate to <value> multiplied by 0.1 millilitres/minute. <value> must be in the range minus 30000 to plus 30000. A positive value inputs water into the borehole.

"?DIR" Requests the current direction of pump movement. The answer is "R" for right and "L" for left.

"?FLW" Requests the current flow rate which should be identical to that given by the "FLOW" command. If it is not then an error has occured. The format of the reply is "OK_<value>" or "AL_<value>". The first indicates that everything is operating correctly whilst the second shows that a positional alarm has been triggered. In this case an "INIT" commend must be received before normal operation can continue. <value> is in the range plus 30000 to minus 30000.

"?POS" Asks for the current position of the pump ram. The answer is in the same format as "?FLW" but in the range 0 to 24000. 0 is at the right and 24000 at the left. A position change of one corresponds to a water volume of 0.033 millilitres.

"?VOL" Asks for the volume pumped since the last request. The reply format is the same as for "?FLW" but in the range minus 32768 to plus 32767. The reply is the number of volume units (0.033 millilitres) pumped since the last request. A positive value shows that water has been injected into the borehole. The flow counter is set to zero at every request and there is no check of counter overflow. It is up to the operator to ensure that pump control is activated at sufficiently close intervals so that overflow cannot occur.

Pump program.

The main program for controlling the pumps is called Stepmot, which together with Motint and Alaint, responds to comands from the main controlling microcomputer and provides flow data. The various sub-routines used by Stepmot are listed below with their functions. In general terms Stepmot starts by initiating all the input and output ports (INITDEVICES) and then checks the input port for commands. If one drops in, the command is executed. Most commands are questions about variable values. In these cases the value is copied to a temporary variable with interupts disabled (to avoid two routines working with the variable at the same time) and then written back to the SIO. The only exceptions are "INIT" and "FLOW_<value>" when INITIALIZE and SETFLOW are called.

INITIALIZE is the routine which calles INITDEVICES to open ports etc. and also moves the ram pump to its starting position. It commences by checking whether the limit controllers (end of ram movement) are active simultaneously. If they are then there is a problem, the initiation is stopped and alarm flags are set. The problem is usually caused by the limit control cable not being connected which activates both signals.

If the hardware is functioning the pump is run to its right limit. To achieve this simple manoeuver the program follows a logical pathway to ensure that all eventualities are covered. Firstly INITIALIZE checks whether the ram is already at the right limit. If so the positioning is skipped. Otherwise the motor is run to the right until an alarm occurs. In the case of the pump ram starting at the left limit an alarm results when leaving the limit, so the motor is always run for a short time with the alarms disabled. When the right limit alarm is activacted the motor stops automatically. The motor is then run to the left to the desired starting position which is then set to count 0 (right position).

SETFLOW is the routine which accepts the "FLOW" value as calculated by the MEASURE program and converts it to a form which can be used by Motint which regulates the speed of the pumps to achieve the required flow rate and direction.

The old flow value is stored in the variable FLOW and changed to NEXTFLOW, the input parameter of the routine. This value is checked to ensure that the rate will not causes resonance of the pump at 80 Hz. If it will, the value is altered. If an alarm is active the value cannot be changed but usually this is not the case and the value is converted to values for the various counters and timers as listed below. FLOW is the range of steps which the stepping motors must move to achieve the desired flow rate. The prescalar and counters A to C contain the data which is used by MOTINT to vary the flow rate.

FLOW	Presc.A	Counter A	Counter B	Counter C
0	-	-	-	-(interupts disabled)
1	16	256	256	1220/(flow*16)
to				
4	16	256	256	1220/(flow*16)
5	16	16	256	1220/flow
to				
79	16	16	256	1220/flow
80	16	16	16	19531/flow
to				
1279	16	16	16	19531/flow
1280	16	16	1	31250/(flow/10)
to				
30000	16	16	1	31250/(flow/10)

The various levels of counters are used to control the number of steps or volume units (0.033 ml) sent to the ram pump and hence the flow rate.

A speed class is also assigned to the FLOW as shown in the following table:-

FLOW	Class number
-30000 to -15000	0
-14999 to -2000	1
-1999 to -1	2
0 to +1999	3
+2000 to +14999	4
+15000 to +30000	5

If this is an ordinary speed change then the calculated values are loaded to the relevant variables and used to control the pumps. However, if the motor is standing still or moving very slowly the interupt routines are restarted. The counters are reloaded with randomly generated low values just to get things started and regulated to the required higher rate by Motint.

INITDEVICES is the routine which initialises all the input/output circuits i.e. SIO,PIO and CTC. It also gives the variables start values and loads the interupt page with the addresses of all the interupt routines.

WRITEVALUE writes VALUE (input parameter) to the SIO in the form "OK_<value>" or "AL_<value>" depending on the alarm.

READINTEGER reads an integer from the SIO to a variable, x. Characters are skipped until a digit or a minus sign is recognised. Then the digits are collected until the first non-digit, which is usually a carriage return. Note that the routine "uses up" the first non-digit after the number, so the end-of-line character immediately following the number disappears.

WRITEINTEGER writes the variable x to the SIO. The number is separated into digits and temporarily stored in a character buffer with the least significant digit stored first. The buffer is then output.

READCHAR reads a character from the SIO. Possible parity bits are masked away and the carriage return is mapped to space.

WRITECHAR writes a character to the SIO.

MOTINT. The function of this control routine is to accelerate or decelerate the pumping rate smoothly when supplied by commands from the measure program. The intended motor speed is stored in the variables flow, the counters preav, ctcav, ctcbv and and ctccv and also in class. The real movement of the motor is stored in aflow and aclass (actual flow and actual class). The variable adelay is a count down counter to make the motor go a certain number of steps prior to changing its speed class.

The routine checks the position of the ram in relation to the limits (left or right) and adjusts speeds accordingly to aid in directional changes. At all times Motint attempts to change the motor speed to that requested by the measure program.

ALAINT. This routine sets the alarm flags and stops the pump motor by resetting the counters if an alarm is detected.